Laser Diagnostics Advances for the Study of Electric Propulsion

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Online Low Temperature Plasma (OLTP) seminar
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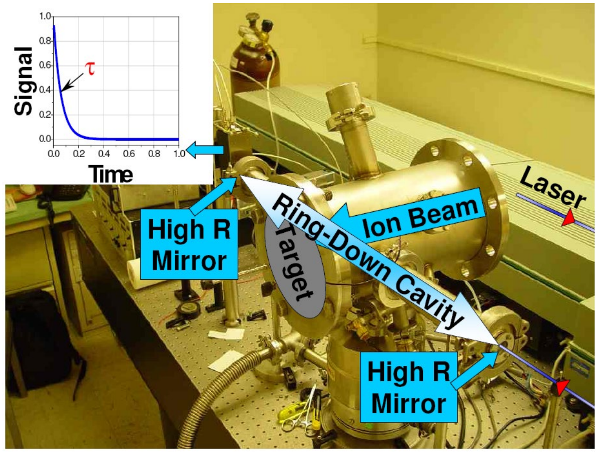
ONLINE LTP SEMINARS
To educate, inform, and connect the LTP community
During the COVID-19 pandemic and beyond
2024

COLORADO STATE UNIVERSITY | DEPARTMENT OF MECHANICAL ENGINEERING
WALTER SCOTT, JR. COLLEGE OF ENGINEERING

Laser Plasma Diagnostics Laboratory / Center for Laser Sensing & Diagnostics

Dept. of Mechanical Engineering, Colorado State University, Fort Collins, CO

- Research Areas:
  - Laser diagnostics for plasma and combustion
  - Plasma engineering: electric propulsion, atmospheric plasmas
  - Laser plasma formation; laser ignition
  - Laser sensors for atmospheric science and monitoring

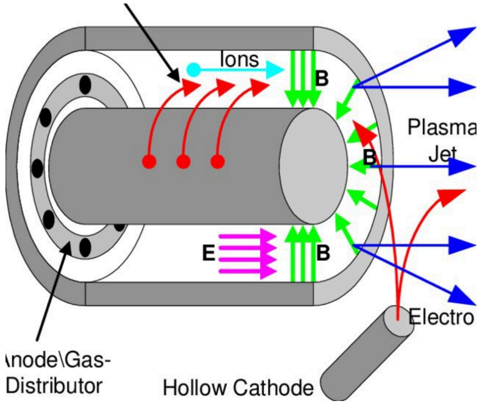


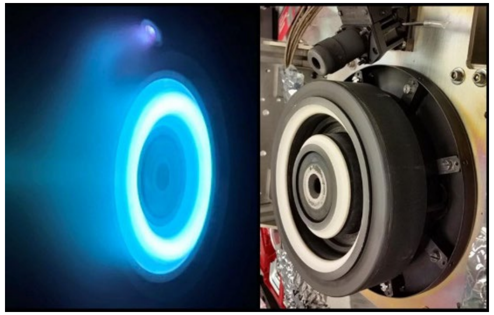
Outline

- Quick introduction to Electric Propulsion (EP)
- Two-Photon Absorption Laser Induced Fluorescence (TALIF) of Neutral Atoms
  - Role of neutrals
  - TALIF overview
  - HET Study: Temporally-resolved TALIF for Neutral Dynamics during Breathing Mode
  - Direct Tagging Velocimetry
- Cavity ring-down spectroscopy (CRDS) of Sputtered Particles
  - Role of sputtering
  - CRDS overview
  - HET study: Erosion of boron nitride insulator channel
- Comact setup for high-sensitivity Thomson Scattering
- Conclusion

Introduction to Electric Propulsion

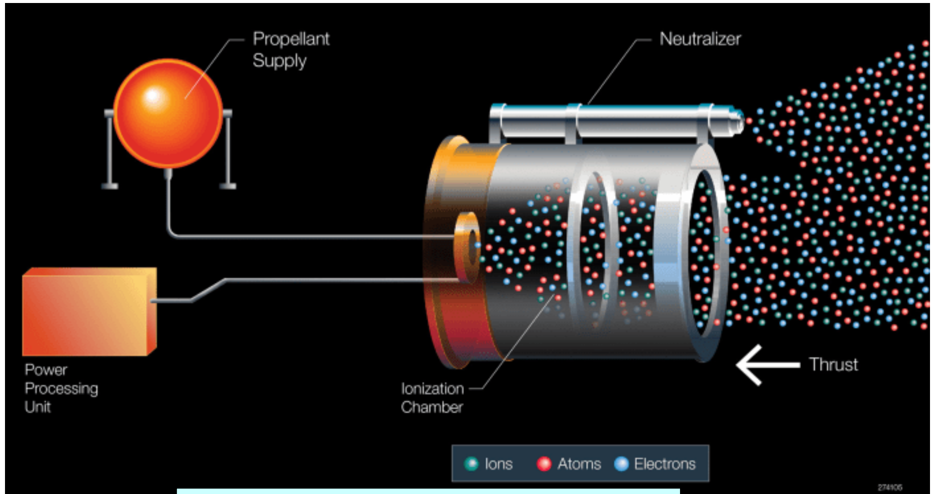
- Electric propulsion (EP) refers to propulsion technologies where electric fields are used to accelerate the propellant.
- Advantages:
  - High-specific impulse
  - Reduced launch mass
  - Long duration capability
- Disadvantages
  - Low thrust
  - Power requirement





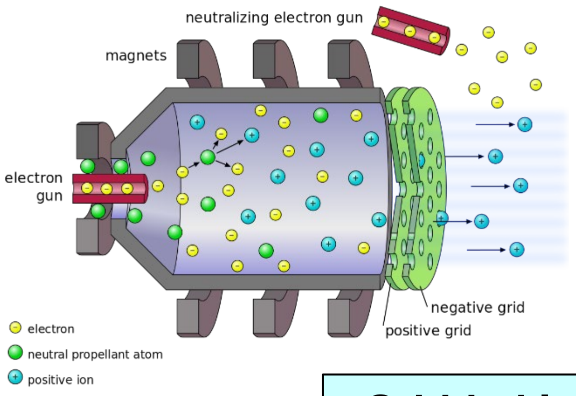
CREDIT: NASA/JPL-Caltech

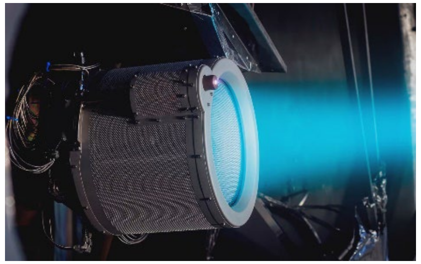
Hall Effect Thruster



Generic EP Thruster

https://www.linkedin.com/pulse/electric-propulsion-basic-concept-herald-sukasi-1c





Gridded Ion Thruster

DART

Double Asteroid Redirection Test

- Planetary defense demonstration of asteroid deflection via kinetic impact
- 7 kW NEXT ion thruster
- Launch Nov. 24th, 2021

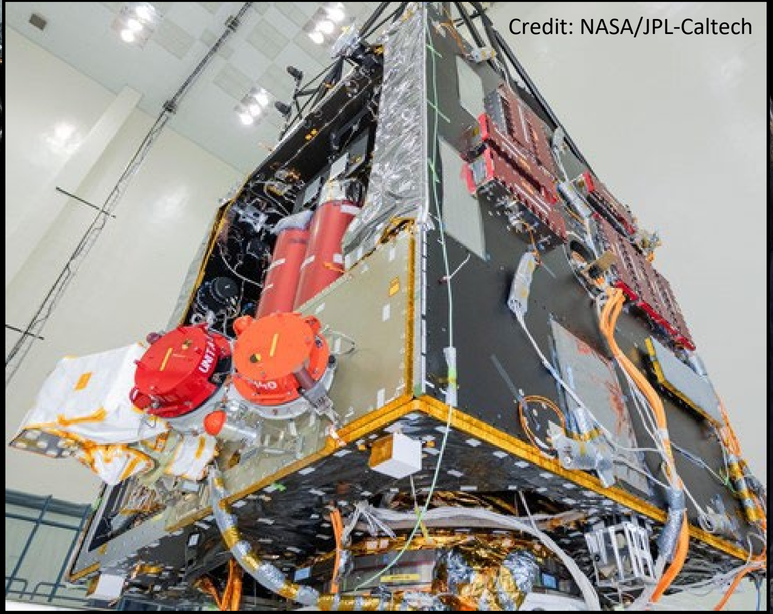
Credit: John Yim / NASA/Johns Hopkins APL

Credit: NASA/Johns Hopkins APL/Ed Whitman

PSYCHE

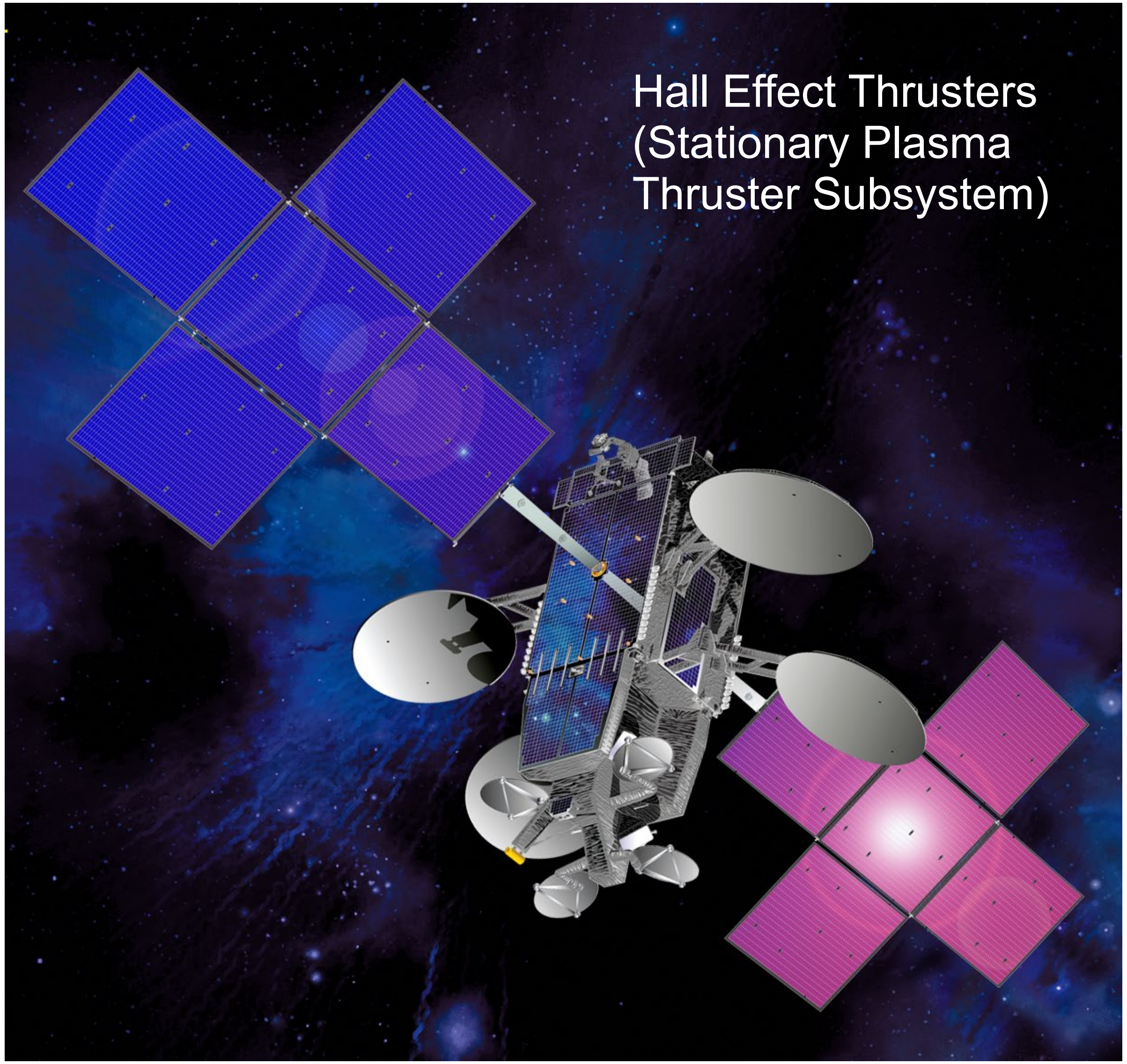
- Exploration of 16 Psyche, metallic asteroid and possible protoplanet core
- Four 4.5 kW SPT-140 Hall
- Launch summer 2022

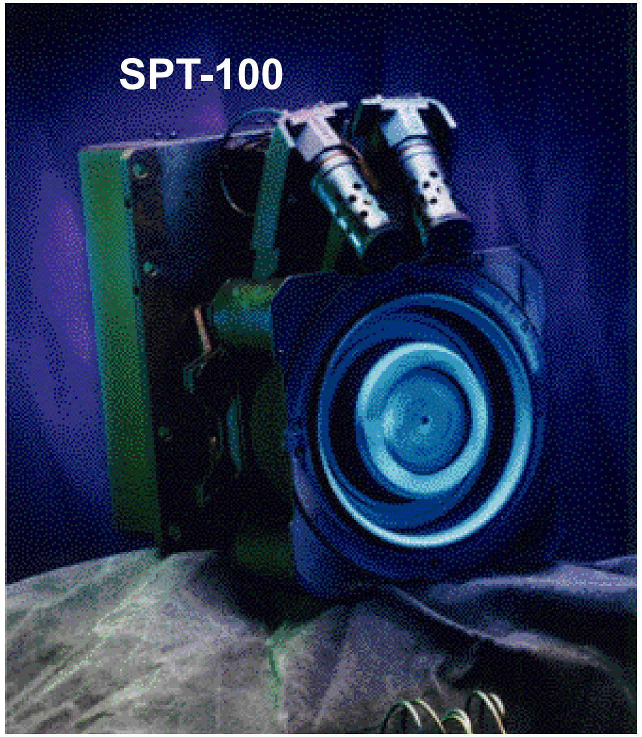
Credit: John Yim / Maxar/ASU/Peter Rubin



Credit: NASA/JPL-Caltech

EP Thrusters on Satellites





Research and Diagnostic Needs

An Overly Short Overview

Applied:

- High-power (and power-density) thrusters
  - Testing and qualification from terrestrial chambers
- Device lifetime
- System level integration, thruster-spacecraft interactions etc.

Basic:

- Crossed-field transport
- Instabilities and oscillations

- Experimental studies performed for frontier studies, device characterization, model validation and development.
  - Physical probes very useful but also have limits in terms of intrusiveness and lack of detailed information.
  - Laser diagnostics can provide detailed data with species specificity, and spatial and temporal resolution.

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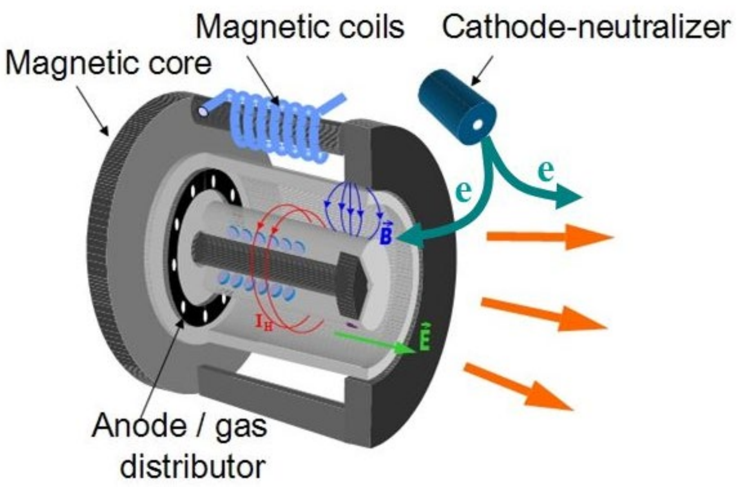
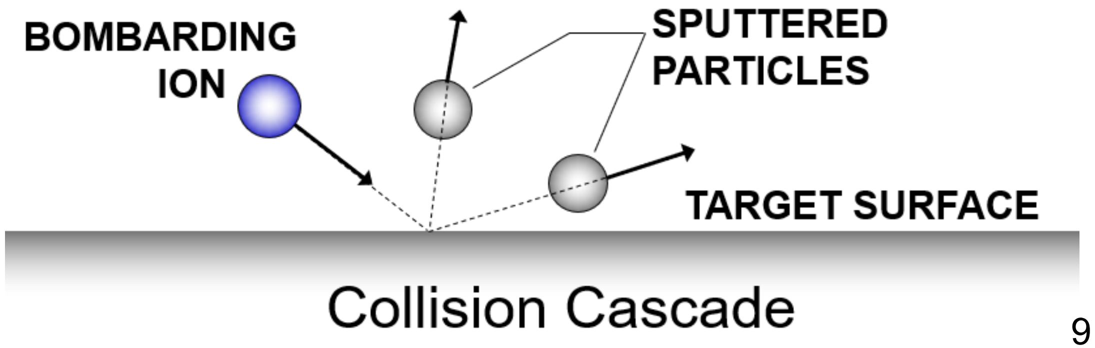
Importance of Neutral Particles in Hall Effect Thrusters

- Neutral particles significantly influence ionization processes, thruster efficiency, interactions with thruster walls, and cathode subsystems. These effects make it difficult to extrapolate from ground test data to in-space operation: Facility Effects. Examples:
  - Ingestion of neutral particles influences thrust.
  - Neutral density levels control the rate of Charge-Exchange Reactions (CEX) which can influence thruster lifetime by changing the sputtering process.
- Instabilities and oscillations play key role in Hall thruster physics and operation.

→ Need for spatially- and temporally- resolved neutral density measurements in thruster plasmas, plumes and facilities.

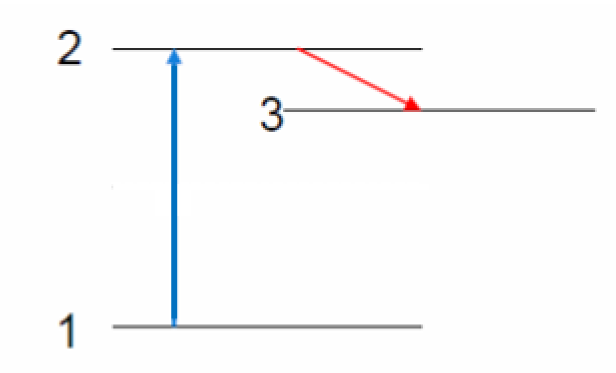


https://htx.pppl.gov/thrusters.html

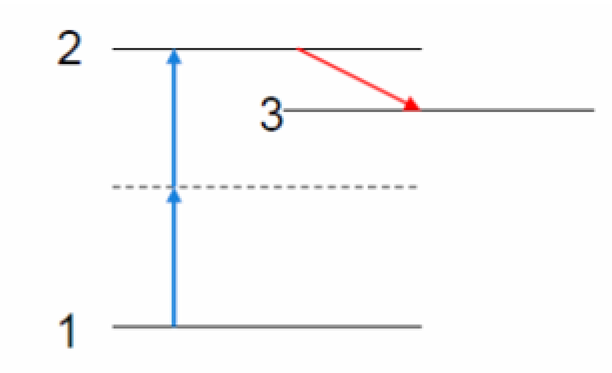


Neutral Atom Measurements by TALIF

- Probe measurements of neutrals are difficult.
- Optical methods, particularly Laser Induced Fluorescence, can be used but should measure the ground state of the neutral atom.
  - ***Why the ground state?***
  - ***To a good approximation:*** $n_{Ground\text{-}State} = n_{Total}$
- Challenge: LIF of ground state Xe requires λ~110-125 nm.
- In TALIF, the atom absorbs two photons simultaneously with λ ~ 220 – 250 nm (exciting atom by the sum of the photon energies), but the process is weak!

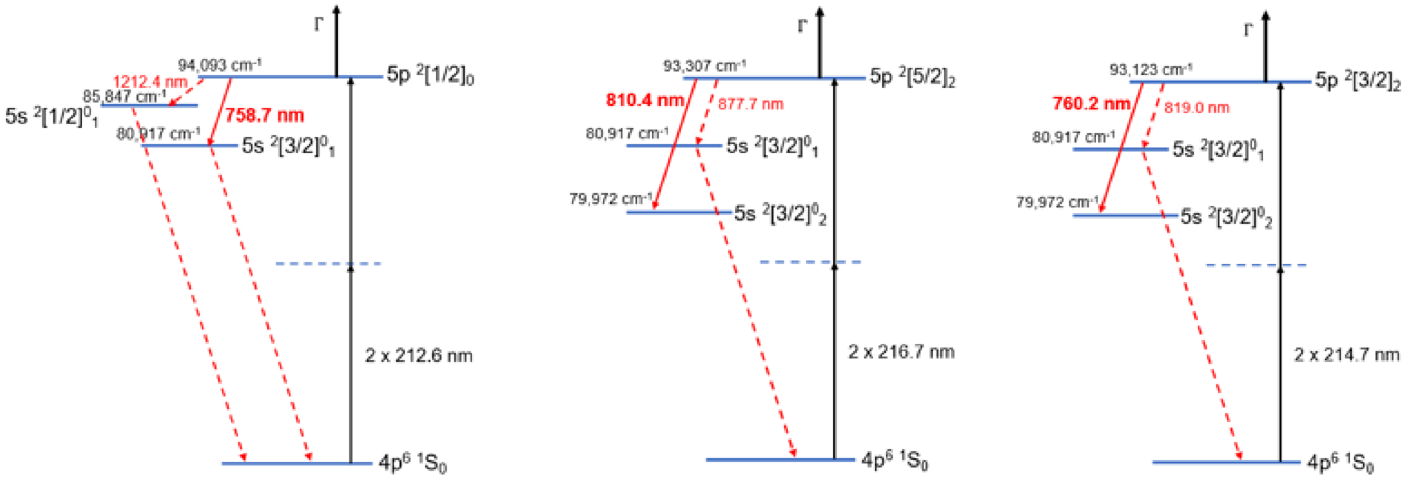


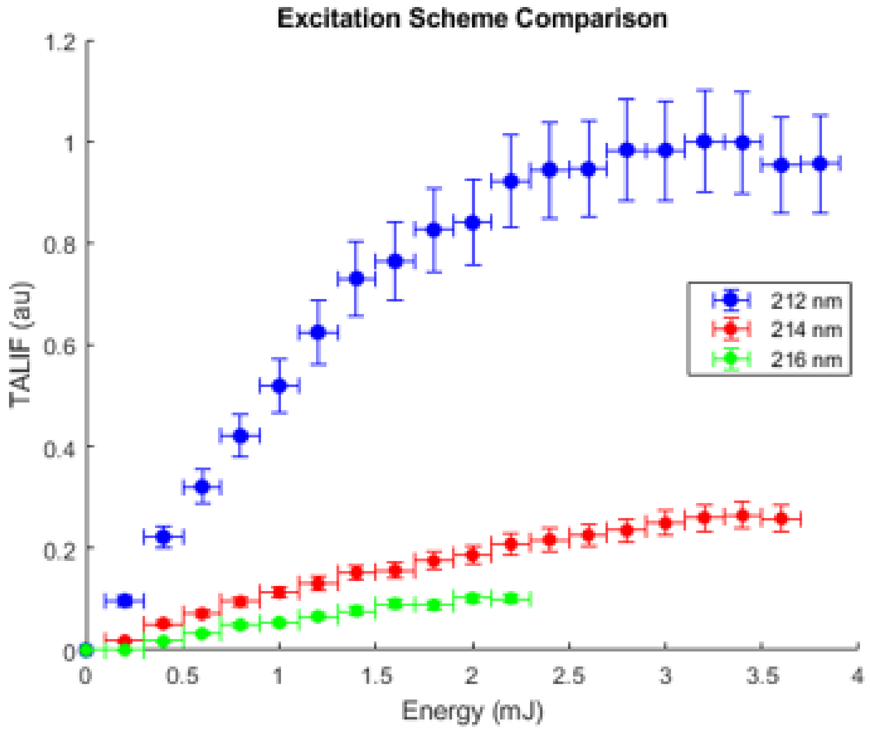
LIF (single-photon)



TALIF

TALIF Schemes for Kr





- TALIF signal dependence on laser energy in agreement with model
- The 212 nm scheme most favorable for high S:N detection

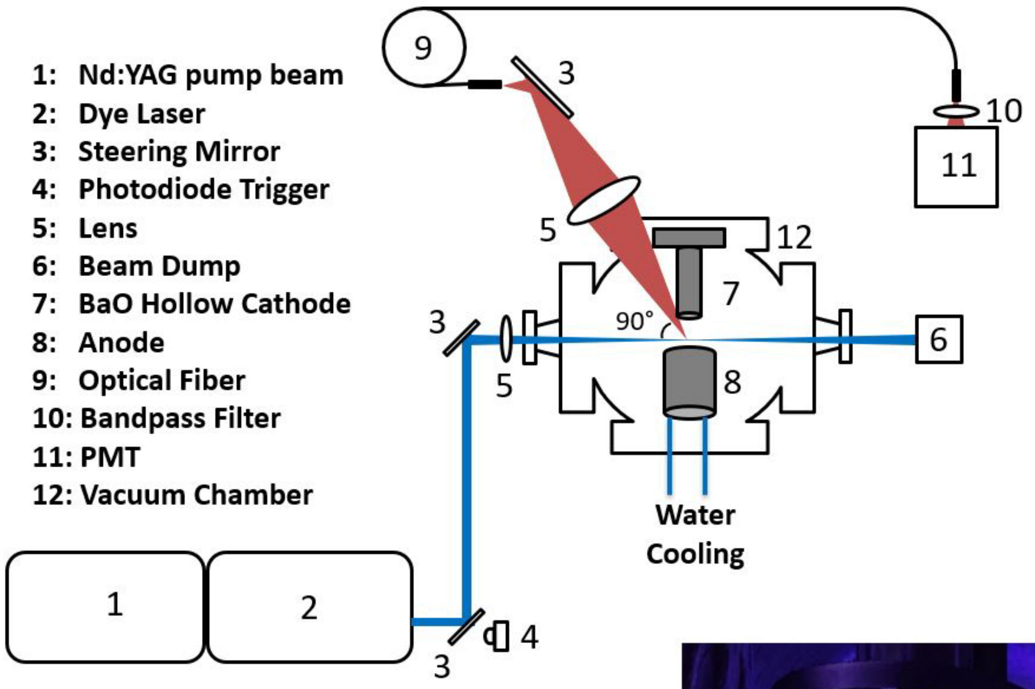
S. Antozzi, et al., AIAA-2023-4269

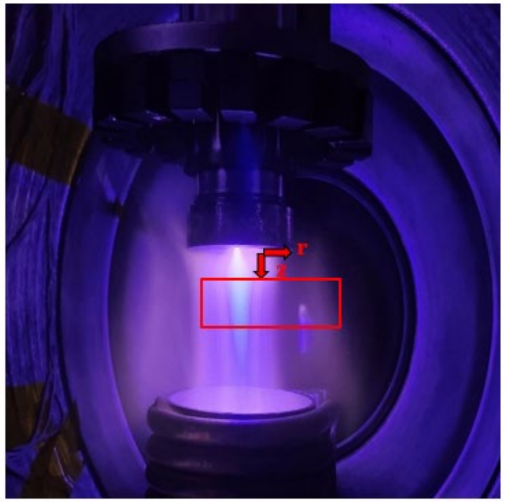
Hollow Cathode TALIF Experimental Setup

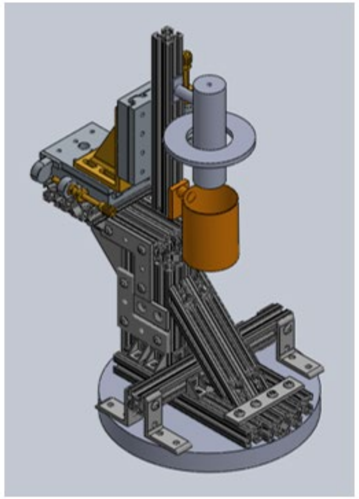
Laser Output	
Wavelength	428 nm doubled to ~212 nm
Linewidth	1.4 pm
Frequency	10 hertz

Collection Setup	
Area	0.3 mm^2
Delivery	600 μm fiber optic
PMT	Gain ~5x10^5

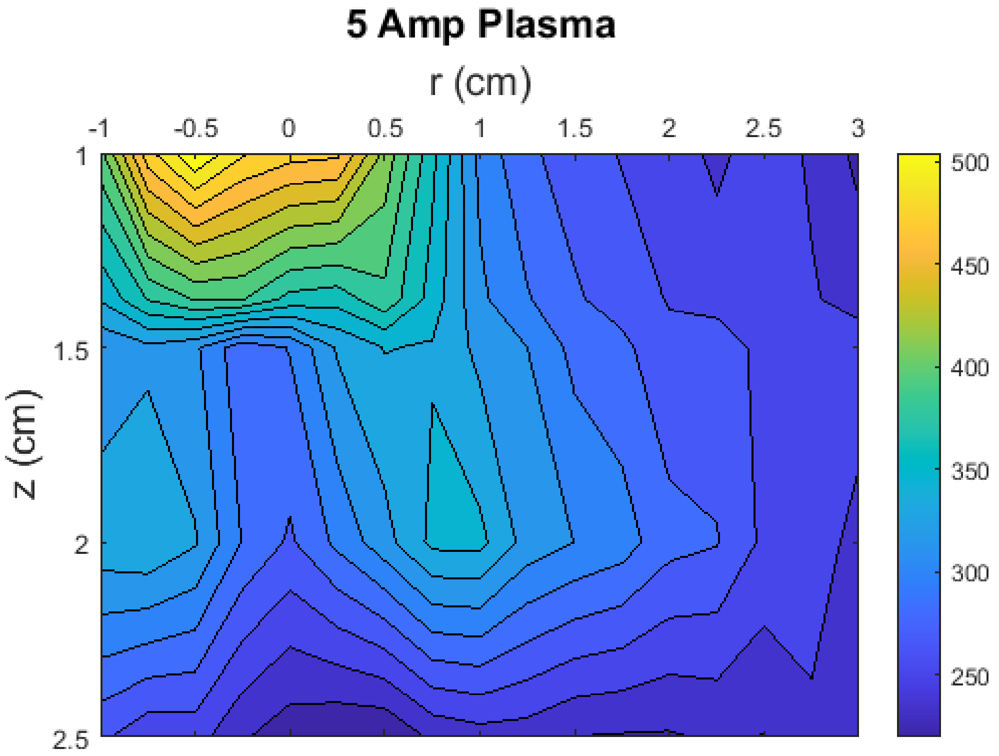
Hollow Cathode Operating Conditions	
Anode	25-40 V; 5, 13 A
Keeper	6-10 V, 1A
Chamber Pressure	~0.3 mTorr

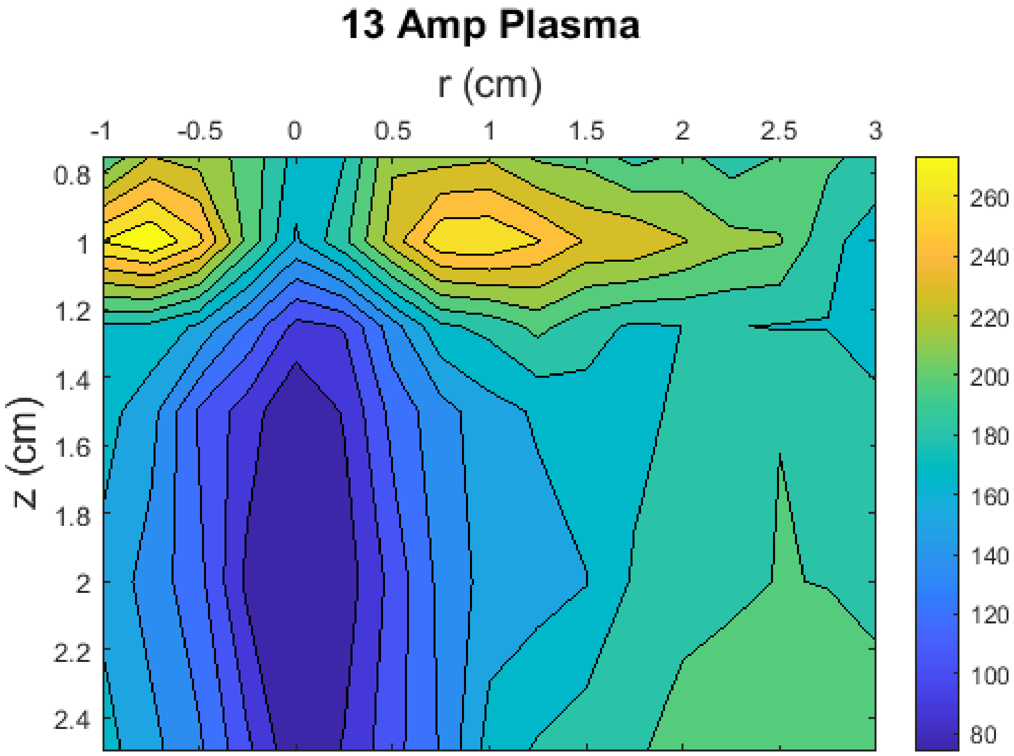






Plasma 2D Spatial Mapping



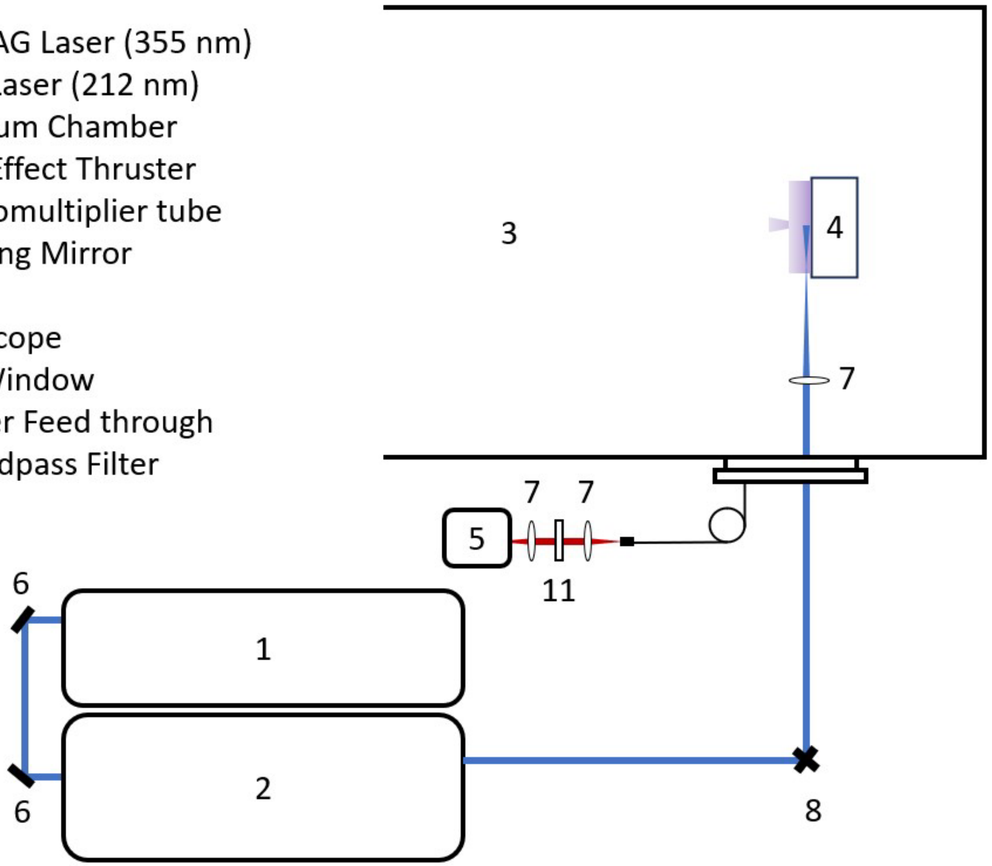


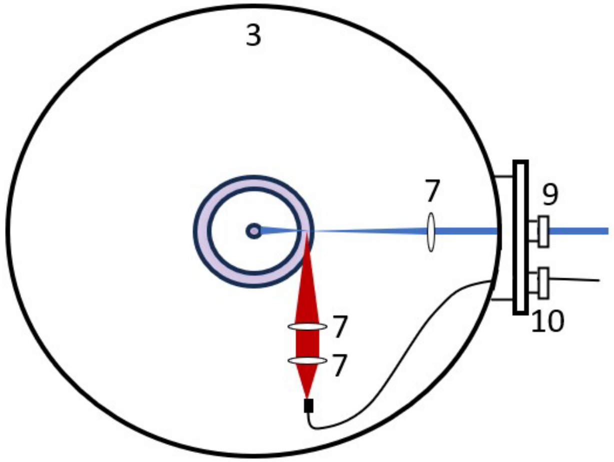
- Neutral depletion region growth with higher currents
- Matches earlier lower resolution spatial profiles from our lab group
- Features of profiles may relate to spot vs. plume mode transition

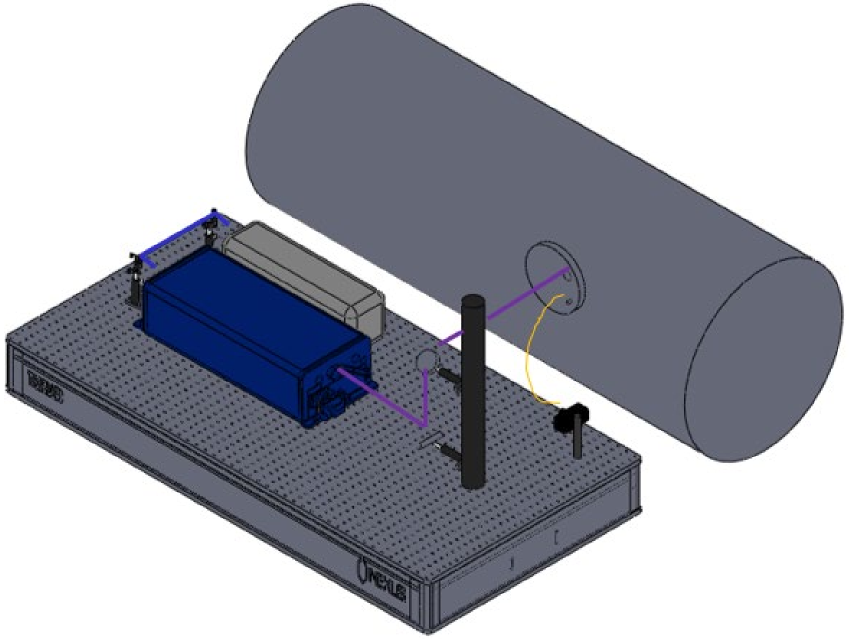
Operating Conditions	
Flow rate	7.5 SCCM
Chamber Pressure	~0.3 mTorr

Hall Thruster TALIF Optical Setup

1: Nd:YAG Laser (355 nm)
2: Dye Laser (212 nm)
3: Vacuum Chamber
4: Hall Effect Thruster
5: Photomultiplier tube
6: Turning Mirror
7: Lens
8: Periscope
9: UV Window
10: Fiber Feed through
11: Bandpass Filter







Time-Resolved Kr TALIF of 1.5 kW HET

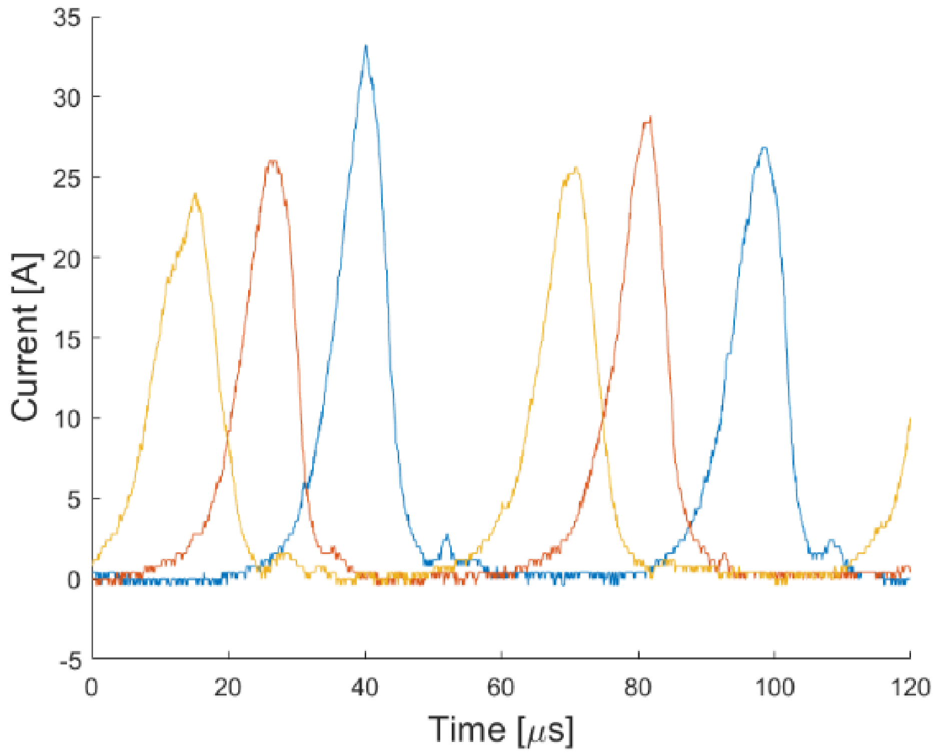
CEPPE Lab
Colorado State University

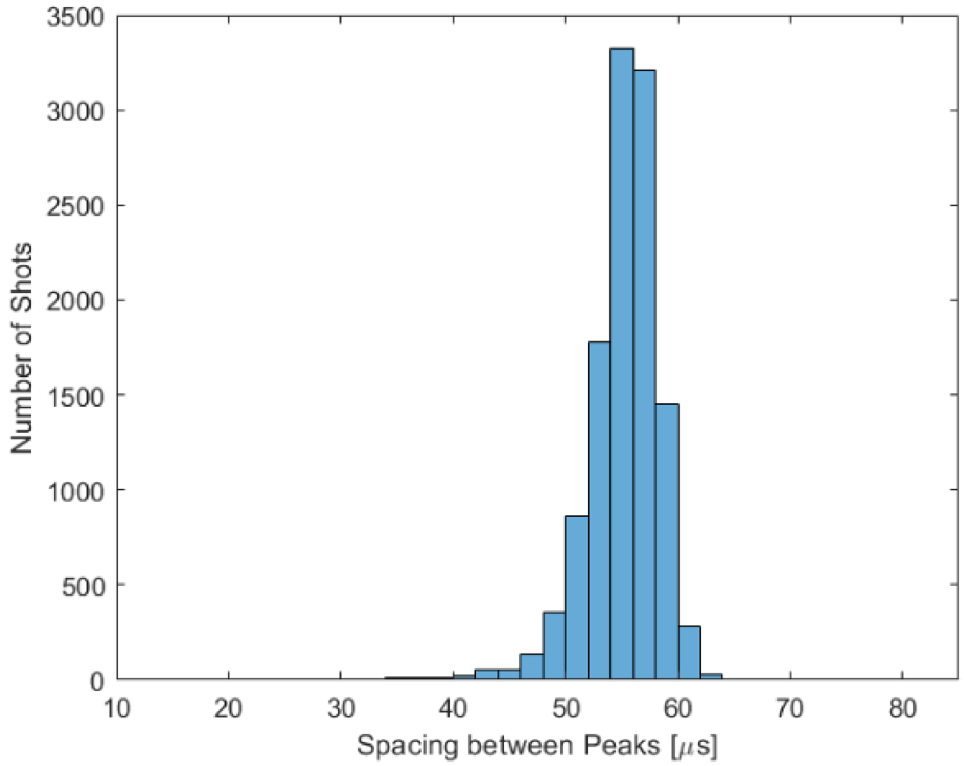
Thruster operating conditions:

- 1.5 kW operation (300 V, 5 A average)
- Anode Flow: 58 SCCM Krypton
- Cathode Flow: 4 SCCM Krypton
- Chamber Base Pressure 7×10^{-7} Torr
- Chamber Operating Pressure: 5×10^{-5} Torr

Measurement Location:
- Channel Centerline
- 5 mm downstream of channel

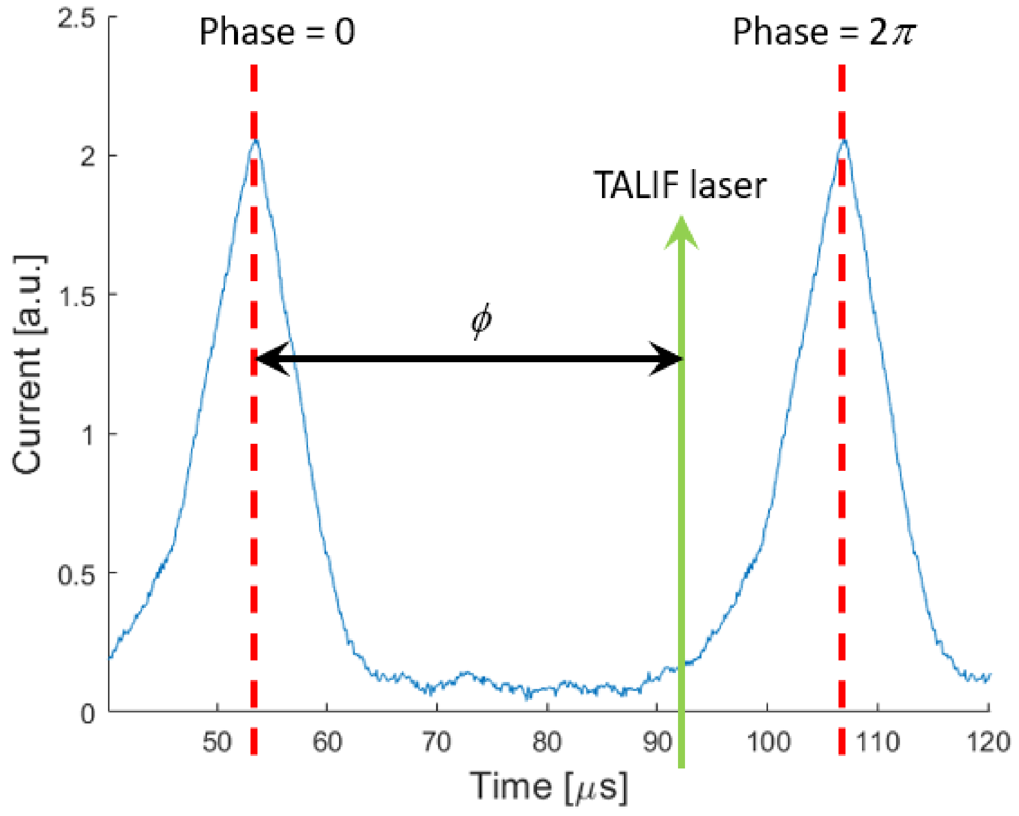
Thruster Oscillations – Breathing Mode





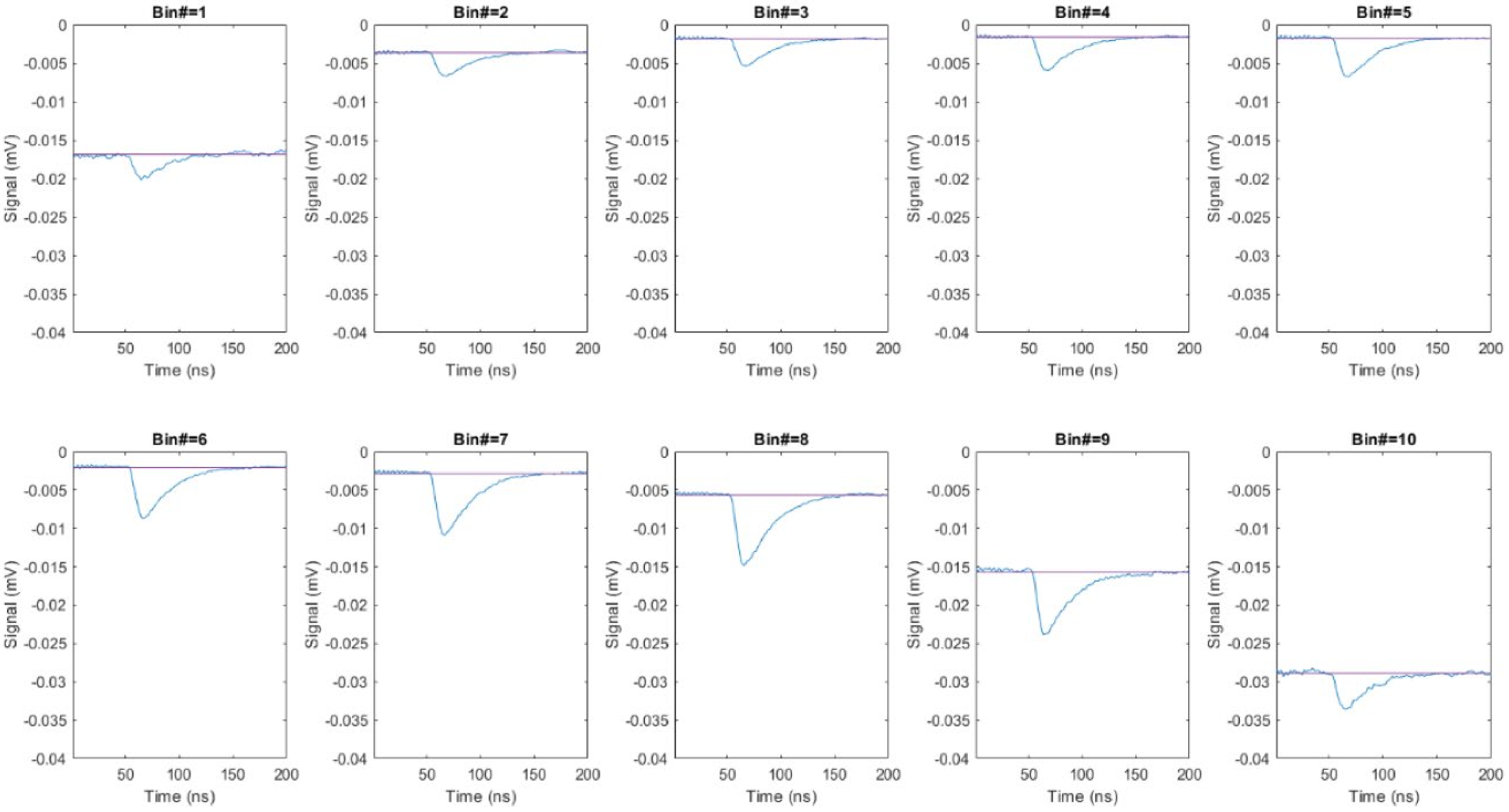
- CEPPE Hall thruster (Brutus) has quite strong and regularly periodic oscillations.
- The oscillations are typical of the Breathing Mode – typical frequencies ~20 kHz
  - Ionization instability ("predator-prey")

Method for Inferring Temporally-Resolved TALIF Signals

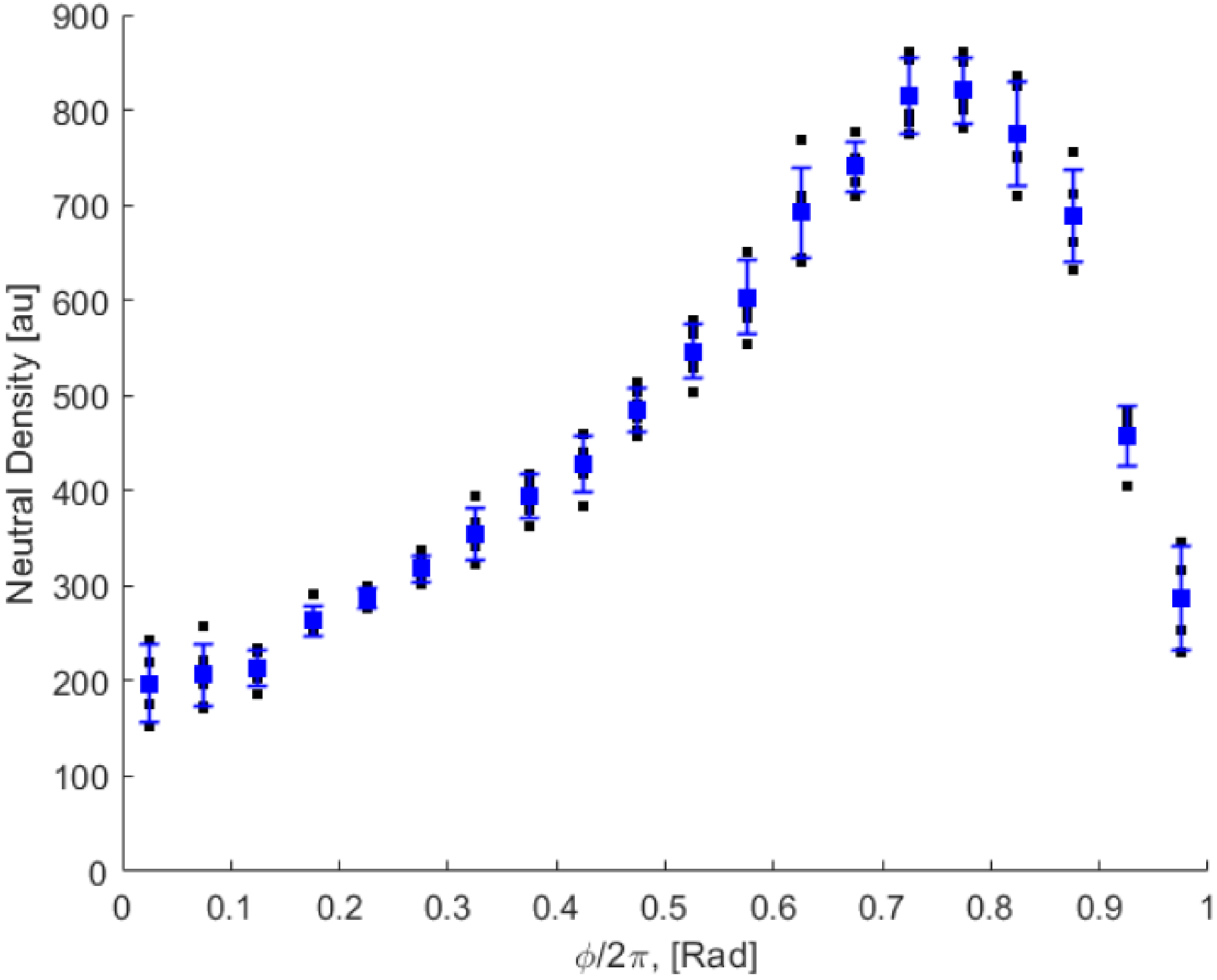


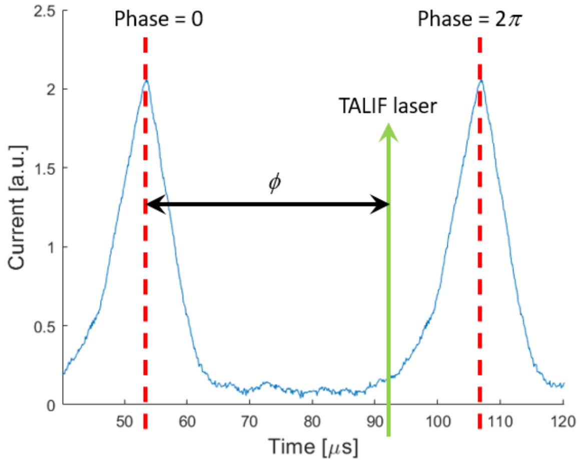
- TALIF laser free-runs at 10 Hz repetition rate.
- Timing of TALIF laser firing and HET current oscillations recorded synchronously.
- Each laser shot is temporally binned based on its phase (simple linear interpolation between peaks).
- Final data analysis bins recorded TALIF signals based on their phase.

Phase-Resolved Raw PMT Signals (10 Phase Bins)

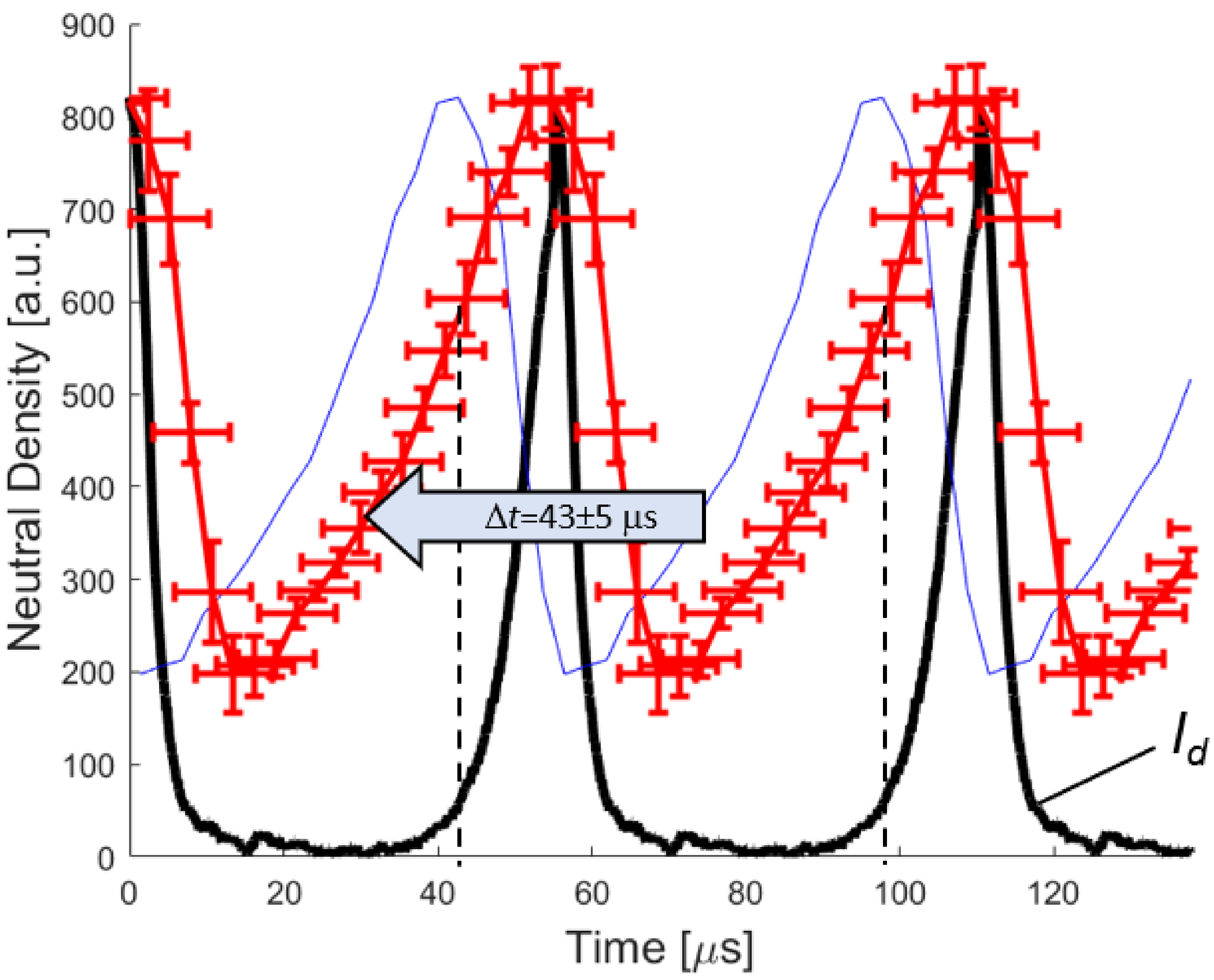


Phase-Resolved TALIF Signal (20 Phase Bins)





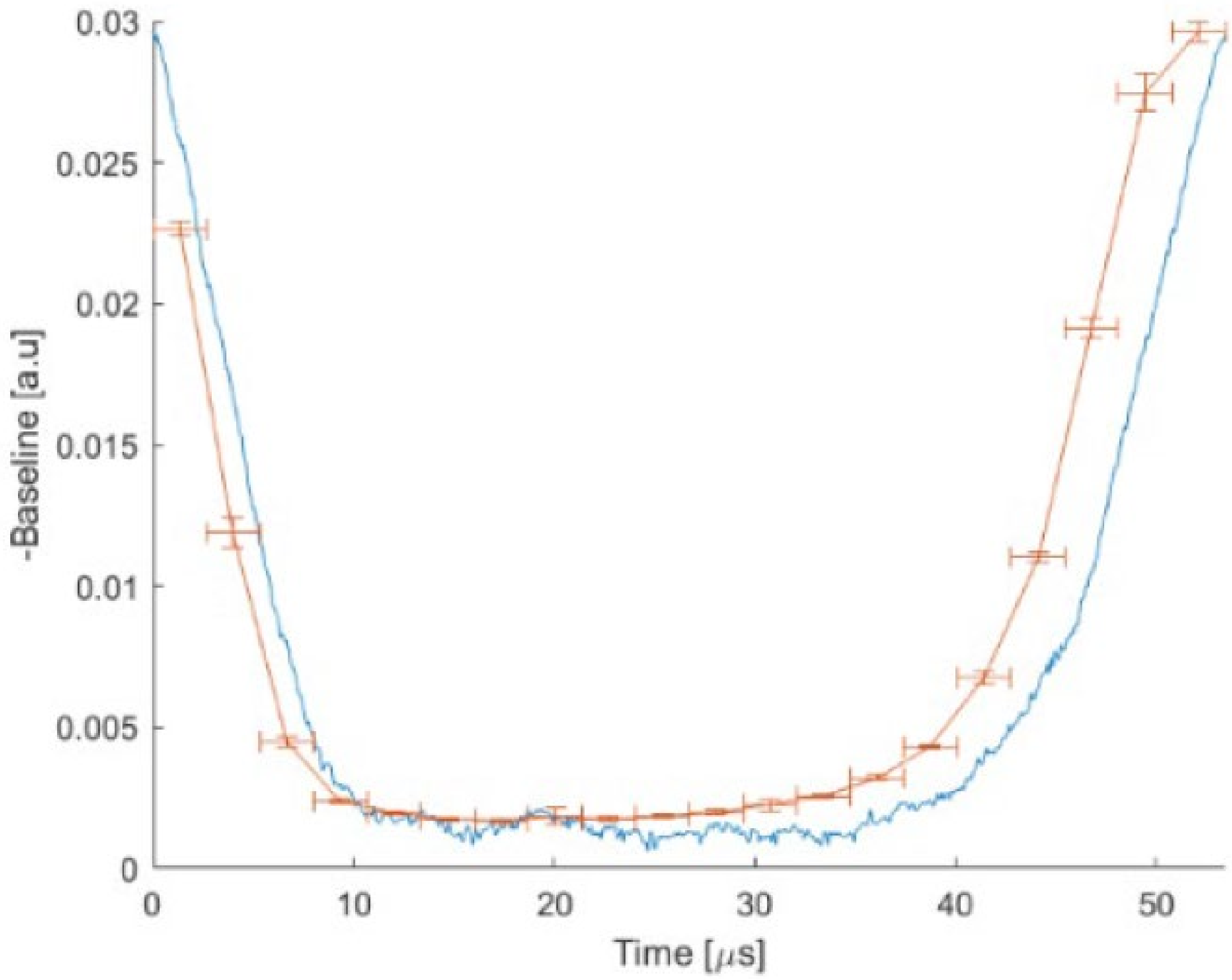
Temporally Resolved Neutral Density over Breathing Mode Oscillation



- TALIF data shifted by time-of-flight $\Delta t \sim L/V$ to describe the neutral density in the ionization region.
- $\Delta t \sim 43$ μs based on thermal velocity of $V \sim 370$-390 m/s ($T_{anode} \sim 550$-600 K) and $L \sim 15$-18 mm between measurement location and end of ionization region.
- Neutral density variation is apparent with phasing consistent with literature.

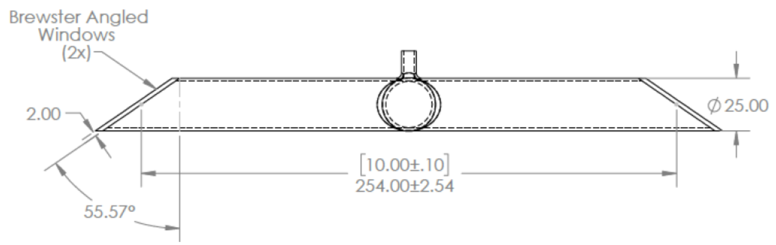
Gottfried et al. "Temporally resolved relative Krypton neutral density during breathing mode of a Hall effect thruster recorded by TALIF" accepted to Journal of Electric Propulsion, 2024

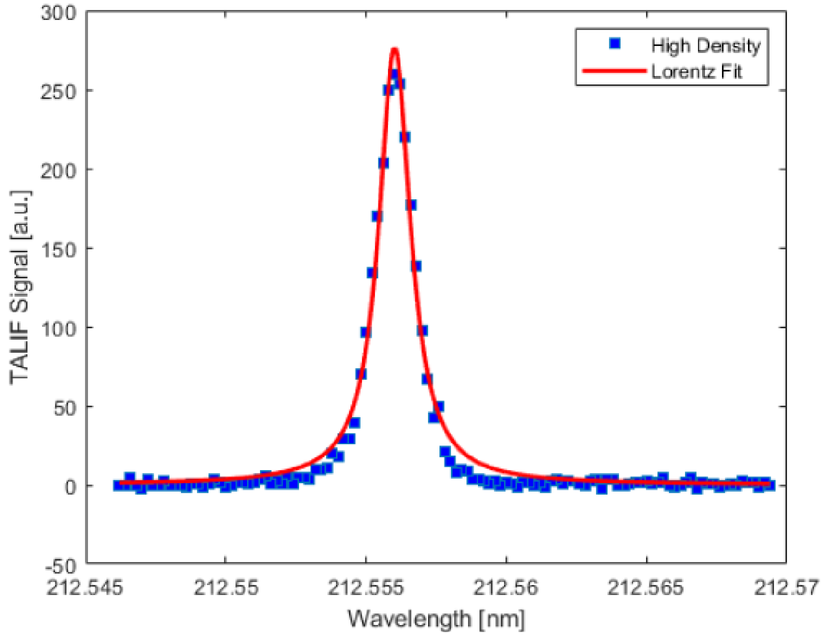
Oscillation of Background Light Emission

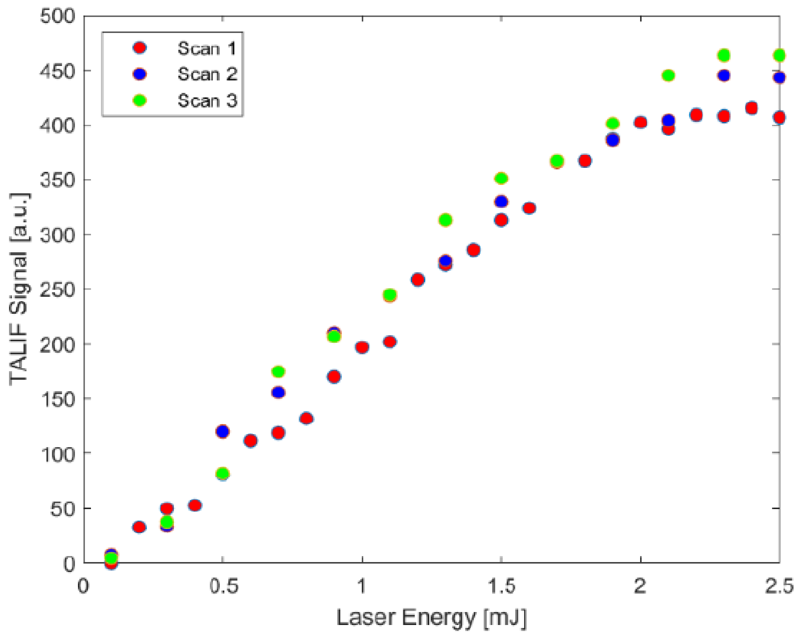


- The TALIF baseline, which is just optical emission from the plasma recorded through the filters, correlates closely with discharge current. [Excited states due to n_e and T_e.]
- The plasma luminosity can be collected quite easily (even with no laser) and may be a useful proxy or check for discharge current

TALIF Signal Calibration by *In Situ* Reference Cells







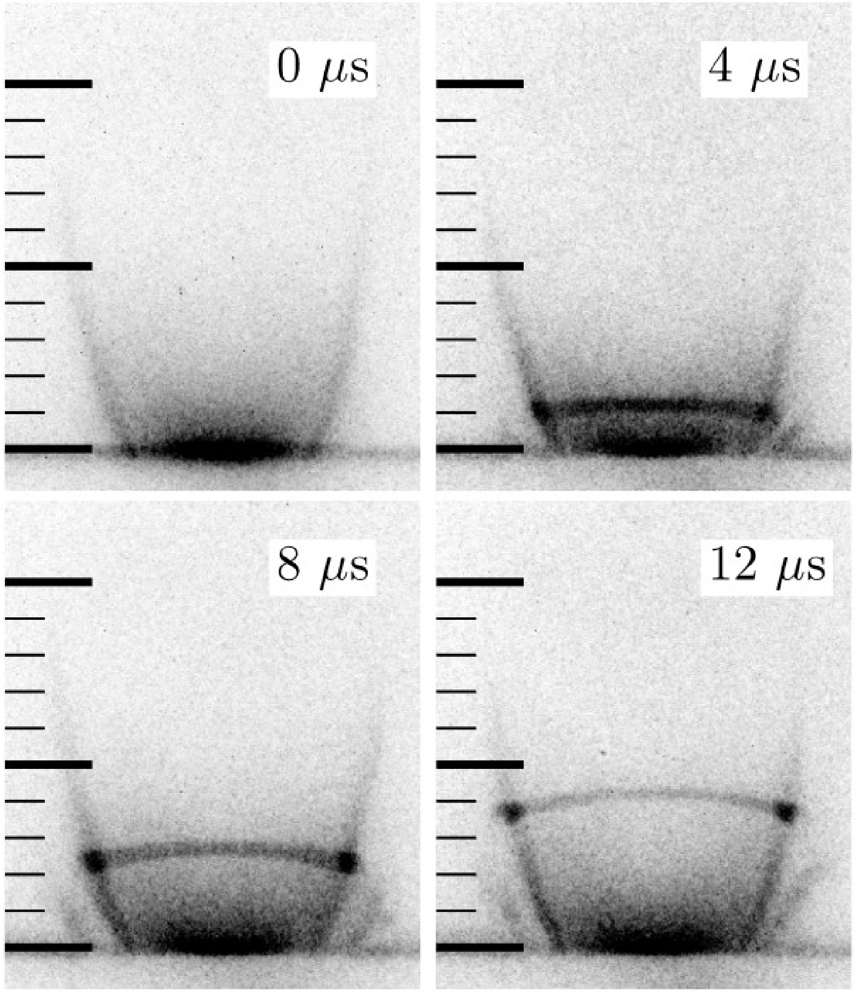
- TALIF signal is linear versus Kr density and can be calibrated via a reference cell implemented in situ in the chamber (same laser energy, focusing, light collection). Data shown is from cell with $n_{Kr}=3.24\times10^{12}$ cm^{-3}.

Extension of Kr TALIF for Neutral Velocimetry

"Read-Write" Molecular Flow Tagging

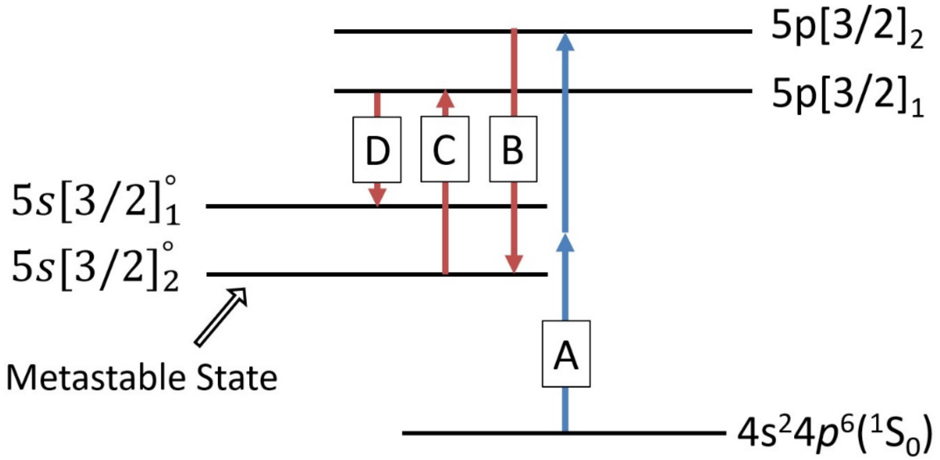
- Krypton Tagging Velocimetry
  - Method for direct measurement of bulk gas velocity
  - Developed for use in low pressure flows (e.g., shock tunnels)
  - Used for atmospheric gases with krypton seeded in at 1-5%
- Performed in Several steps:
  - **Write Step:** Excite ground state krypton by laser absorption (TALIF by 1st beam)
  - **Intermediate Step:** Excited atoms fluoresce into a *metastable state*
  - **Read Step:** Excite atoms in meta-stable state through laser absorption (2nd beam)
  - **Detect**: Image the fluoresced light from the excited atoms

$$V = \frac{dx}{dt}$$

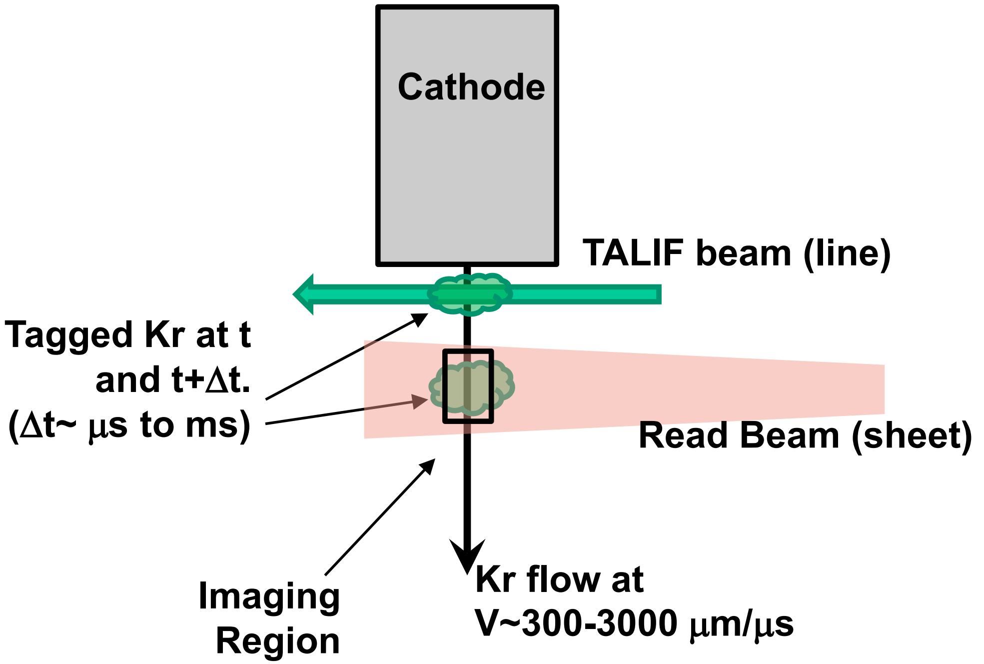


N. J. Parziale, M. S. Smith, and E. C. Marineau, "Krypton tagging velocimetry of an underexpanded jet," Appl. Opt. 54(16), 5094 (2015).

Kr TALIF Flow Tagging Scheme for Velocimetry

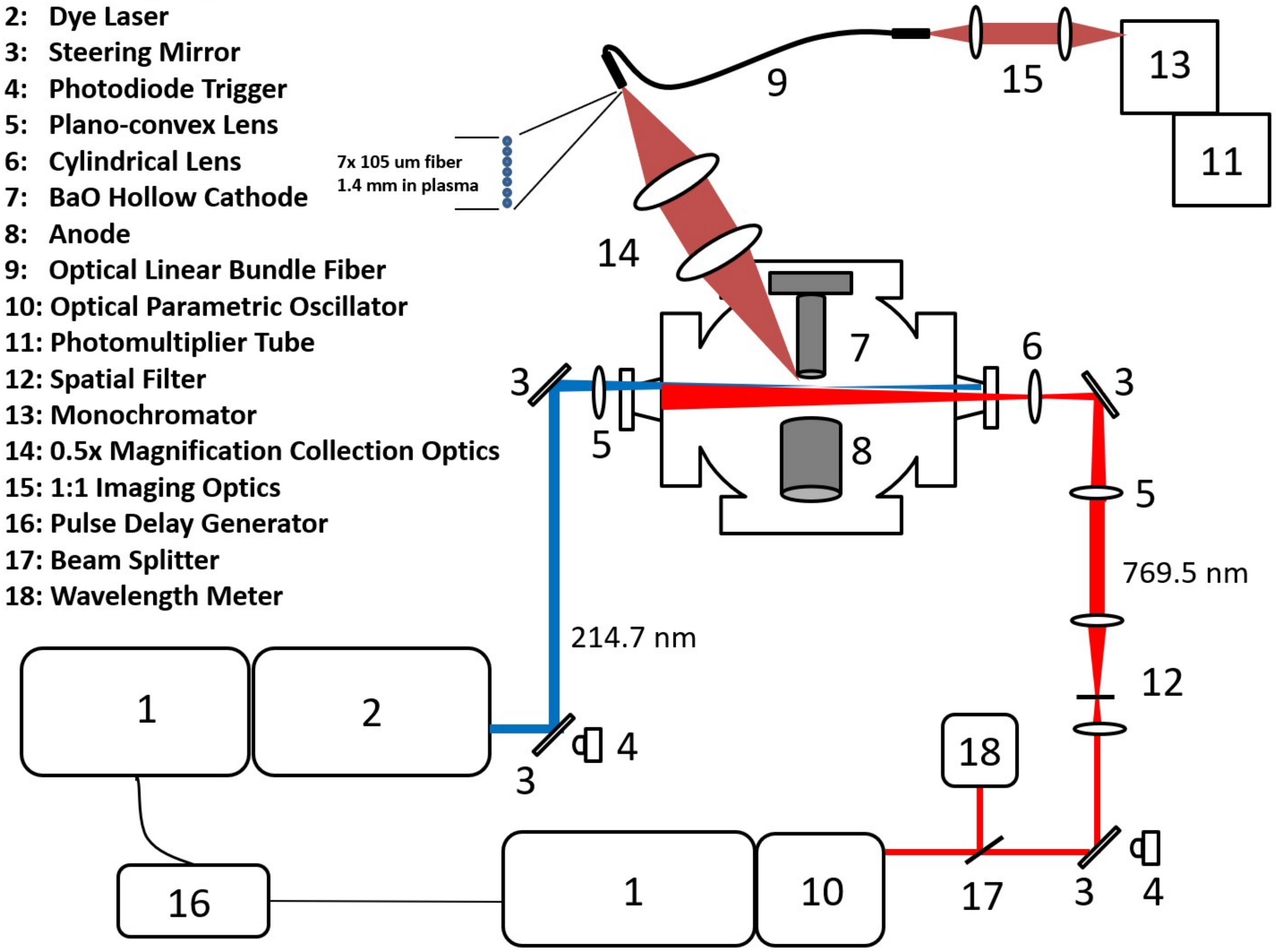


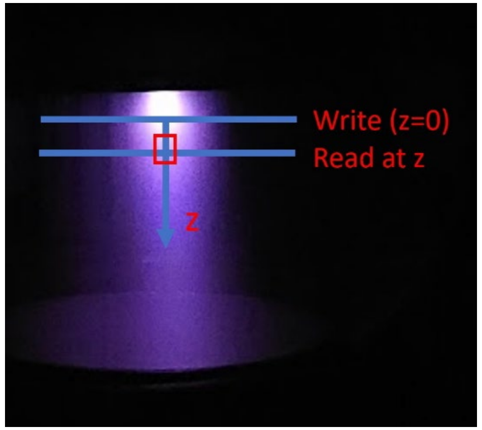
TRANSITION	λ_{Air} [NM]	NATURE	A_{ik} $[s^{-1}]$	E_i $[cm^{-1}]$	E_k $[cm^{-1}]$	LOWER LEVEL	UPPER LEVEL
A	214.7	Two-Photon	-	0	93123.34	$4s^2 4p^6(^1S_0)$	$5p[3/2]_2$
B	760.2	Single-Photon	2.732e7	79971.74	93123.34	$5s[3/2]^\circ_2$	$5p[3/2]_2$
C	769.454	Single-Photon	4.27e6	79971.74	92964.39	$5s[3/2]^\circ_2$	$5p[3/2]_1$
D	829.811	Single-Photon	2.9e8	80916.76	92964.39	$5s[3/2]^\circ_1$	$5p[3/2]_1$



Optical Layout for Velocimetry of Cathode Plume

1: Nd:YAG pump beam
2: Dye Laser
3: Steering Mirror
4: Photodiode Trigger
5: Plano-convex Lens
6: Cylindrical Lens
7: BaO Hollow Cathode
8: Anode
9: Optical Linear Bundle Fiber
10: Optical Parametric Oscillator
11: Photomultiplier Tube
12: Spatial Filter
13: Monochromator
14: 0.5x Magnification Collection Optics
15: 1:1 Imaging Optics
16: Pulse Delay Generator
17: Beam Splitter
18: Wavelength Meter





Heaterless BaO cathode (from CEPPE)

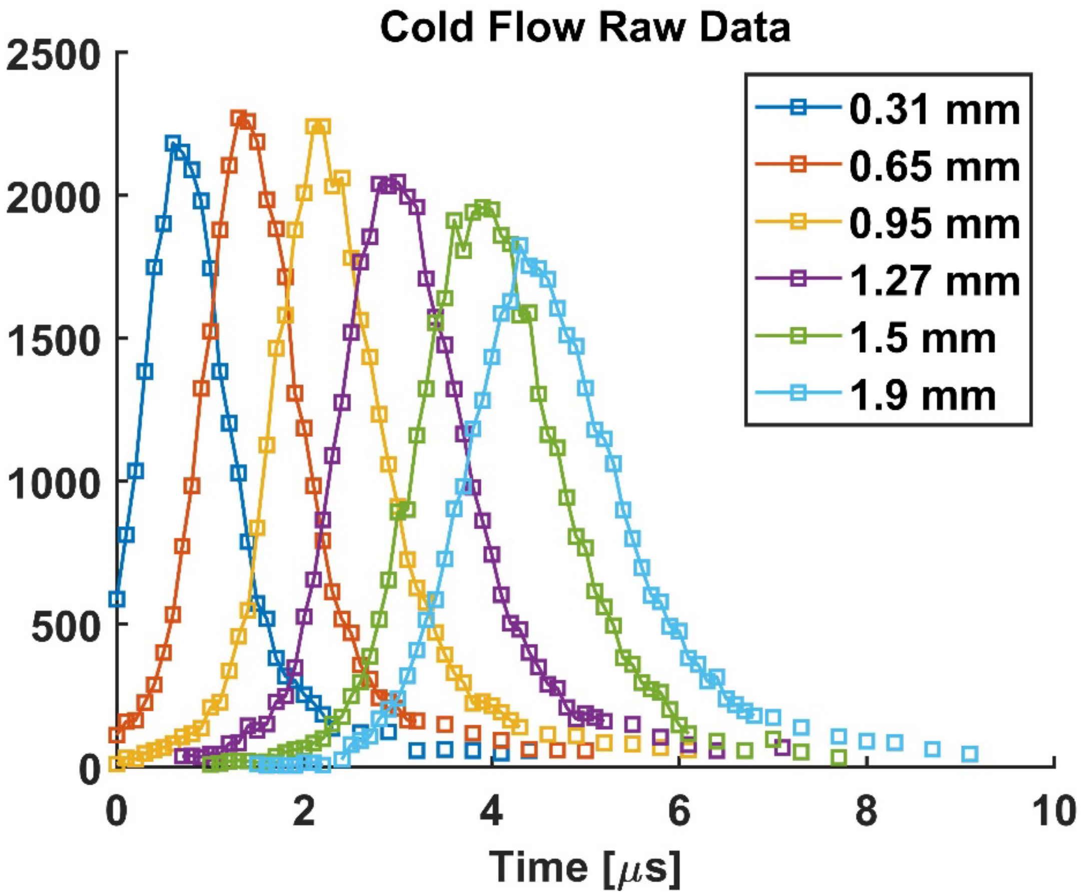
- Krypton Gas – 15 SCCM flowrate
  - 5 A anode Current (~ 45 V)
  - 1 A keeper Current (~ 7 V)
- 2 mm Cathode orifice, 1 mm keeper orifice
- Write Location 7.5 mm below keeper orifice plate

Read Fiber Locations:

z=0.31, 0.63, 0.95, 1.27, 1.5, 1.95 mm

- Region imaged with fiber:
- 200 µm height x 1.4 mm length

Cold Flow: Raw Data and Analysis



- Each trace is the signal versus time at a different read (fiber) location, *z*

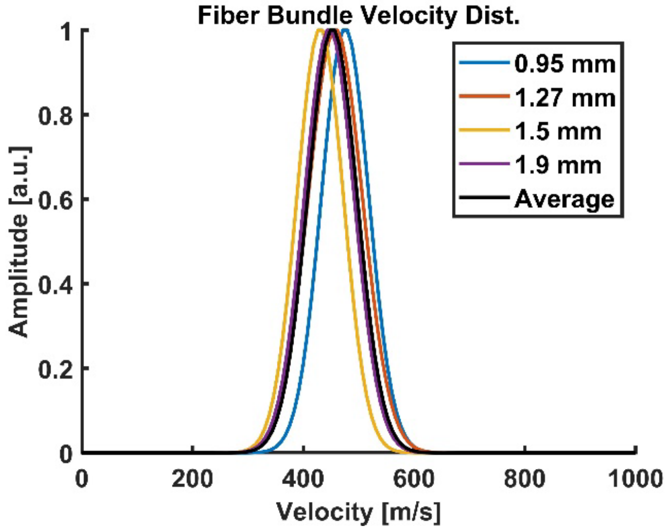
Analysis:

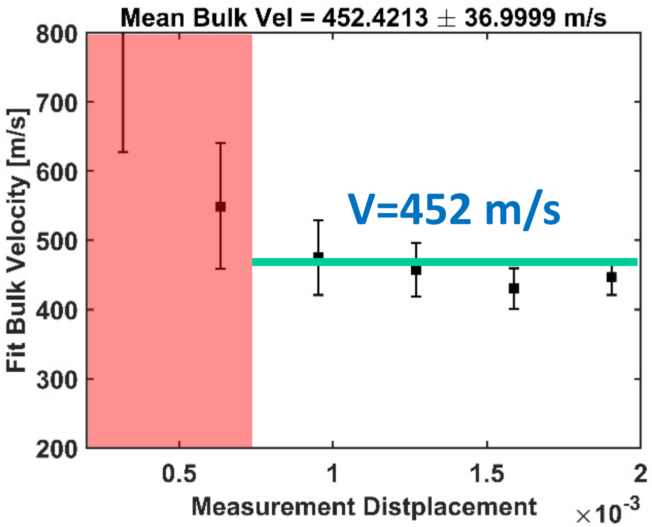
- The **location of the peak is a rough measure of the mean velocity, while the broadening carries information on the velocity distribution**.
- Use 2 free parameters (T, V_B) to create multiple possible VDFs. Search for the VDF giving the best (least-squares) agreement with data:

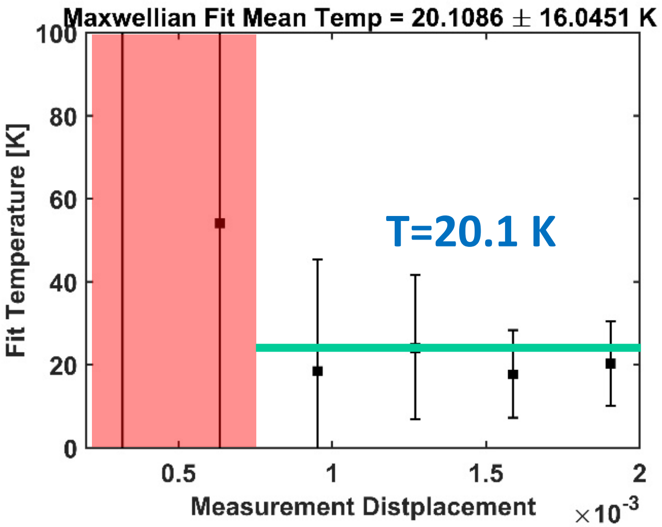
$$f(V_z) = e^{\frac{-m_{Kr}(v_z - v_d)^2}{2kT}}$$

  - Detail: Need to deconvolve fiber effect. Neglect fibers that are too close to Write beam.

Velocity Distribution for Cold Flow



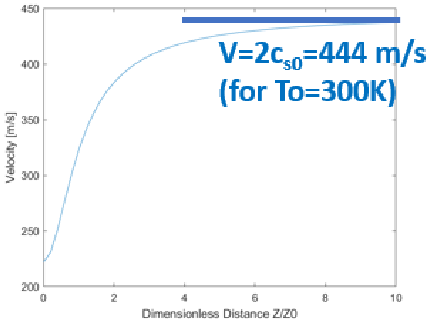




- High signal-noise in cold flow.
- Consistent velocities measured at the different downstream locations.
  - Results consistent with past work on expanding flows at vacuum conditions.

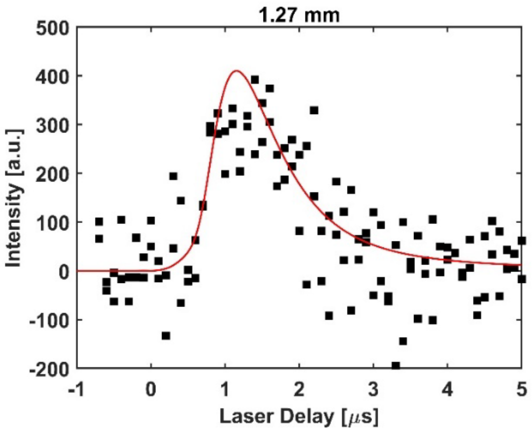
forces) and assuming an adiabatic expansion, the following relation for the velocity w_z on the jet axis can be deduced [18]

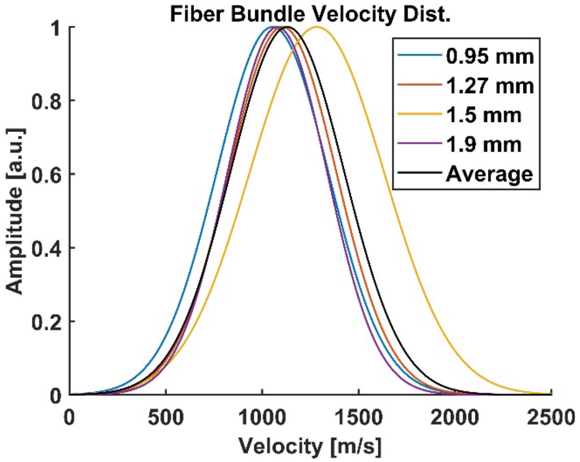
$$w_z = c_{s_0}\left\{1 + \frac{2}{\gamma - 1}\left[1 - \left(\frac{1}{1 + (z/z_0)^2}\right)^{\gamma - 1}\right]\right\}^{1/2}. \quad (4)$$

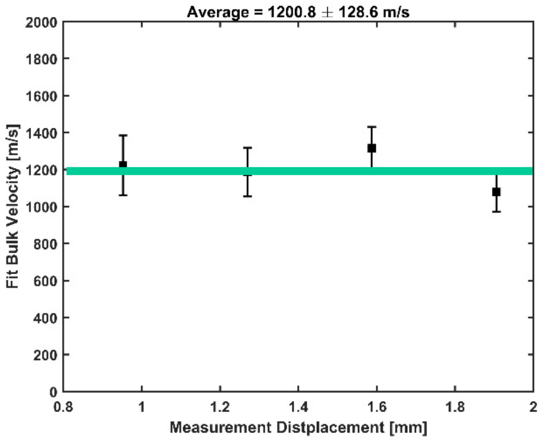


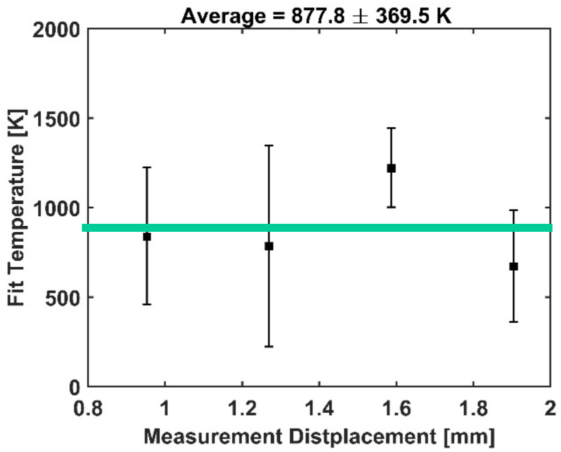
Engeln et al. “Flow dynamics and invasion by background gas of a supersonically expanding thermal plasma” PSST 2001

Velocity Distribution for Plasma

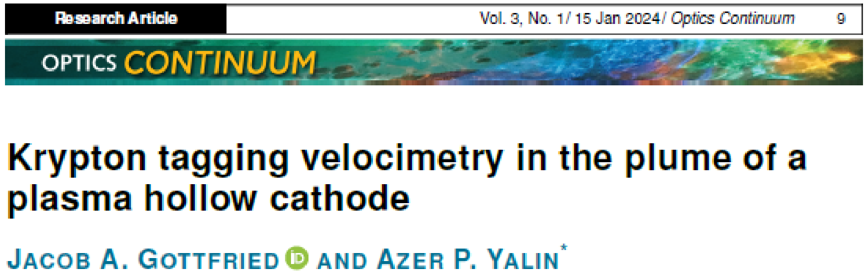








- Noisier due to laser excitation of metastables not created by WRITE laser.
  - Should implement approaches for improved light collection (e.g., c-w READ laser)
- No published data on neutral krypton temperature or velocity for hollow cathode operation
- Results appear consistent with past work:
  - Engeln et al. (2001) used LIF to measure neutral argon in a thermal expanding plasma finding V~2000 m/s and T~1000 – 3000 K


Research Article

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OPTICS CONTINUUM

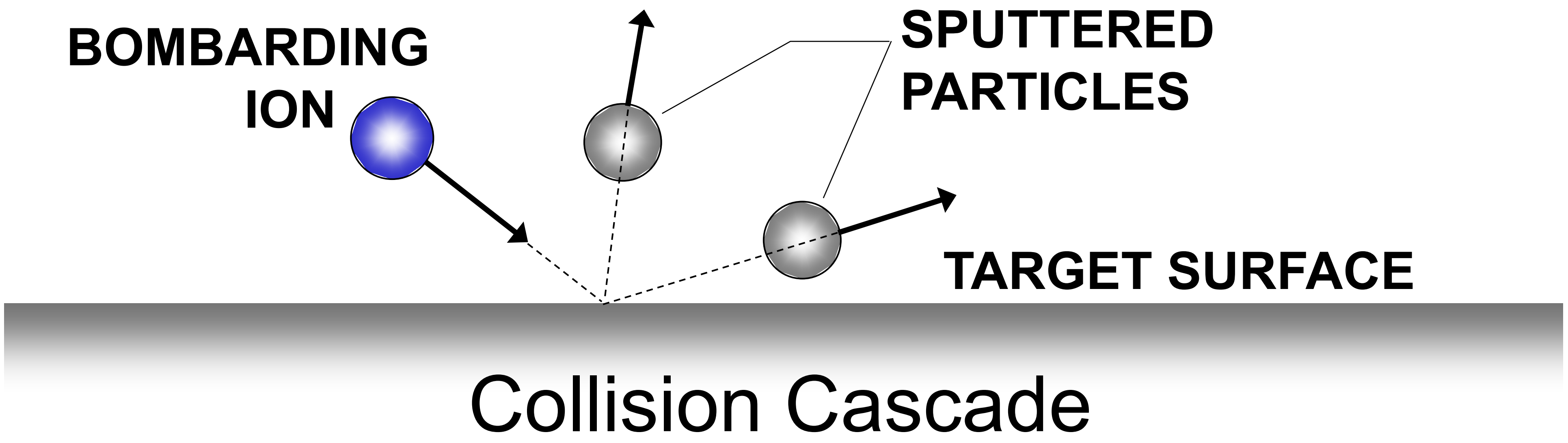
Krypton tagging velocimetry in the plume of a plasma hollow cathode

JACOB A. GOTTFRIED AND AZER P. YALIN*

Outline

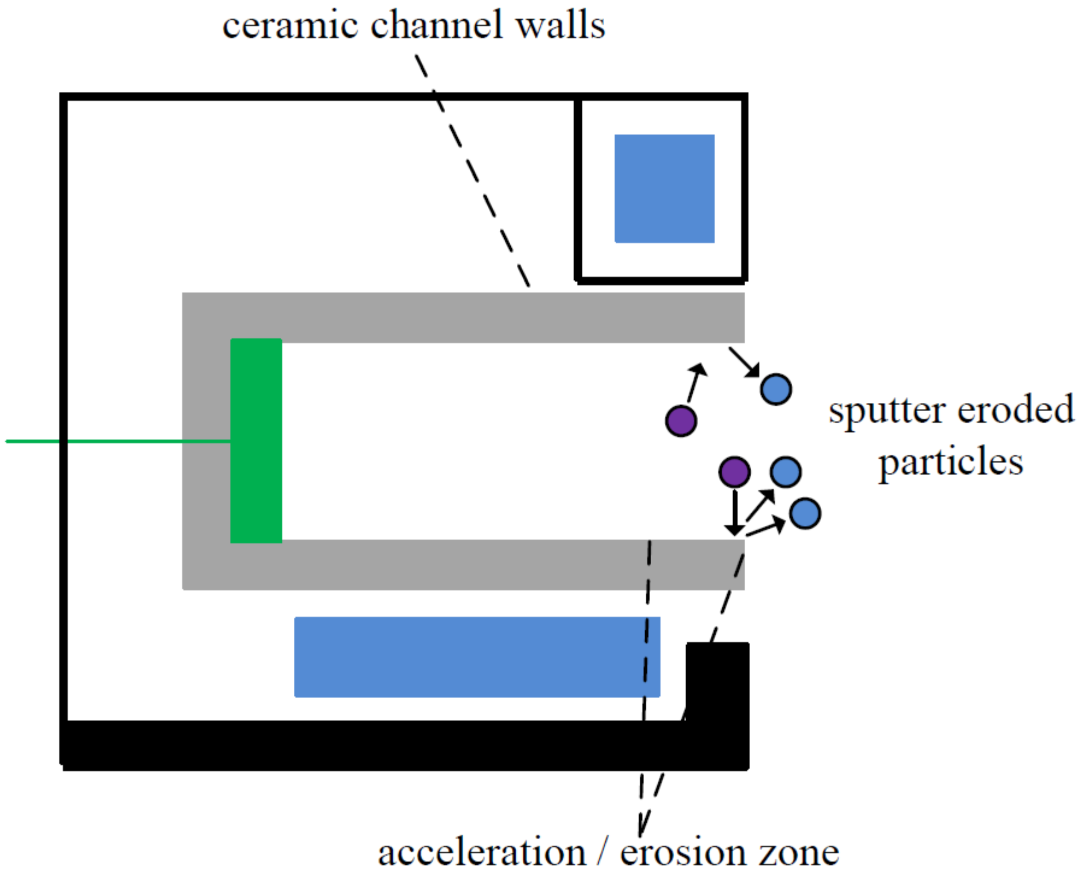
- Quick introduction to Electric Propulsion (EP)
- Two-Photon Absorption Laser Induced Fluorescence (TALIF) of Neutral Atoms
    - Role of neutrals
    - TALIF overview
    - HET Study: Temporally-resolved TALIF for Neutral Dynamics during Breathing Mode
    - Direct Tagging Velocimetry
- Cavity ring-down spectroscopy (CRDS) of Sputtered Particles
    - Role of sputtering
    - CRDS overview
    - HET study: Erosion of boron nitride insulator channel
- Comact setup for high-sensitivity Thomson Scattering
- Conclusion

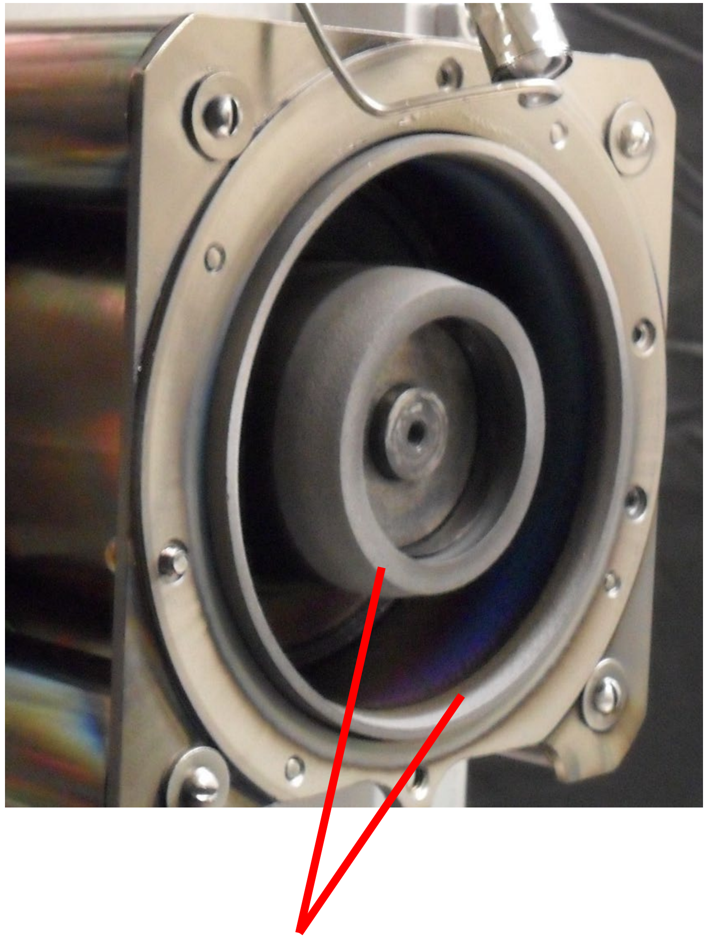
Ion Sputtering



Sputtering is a rich physical phenomenon with applications including electric propulsion, nuclear fusion, and manufacturing of optical and magnetic layers and films.

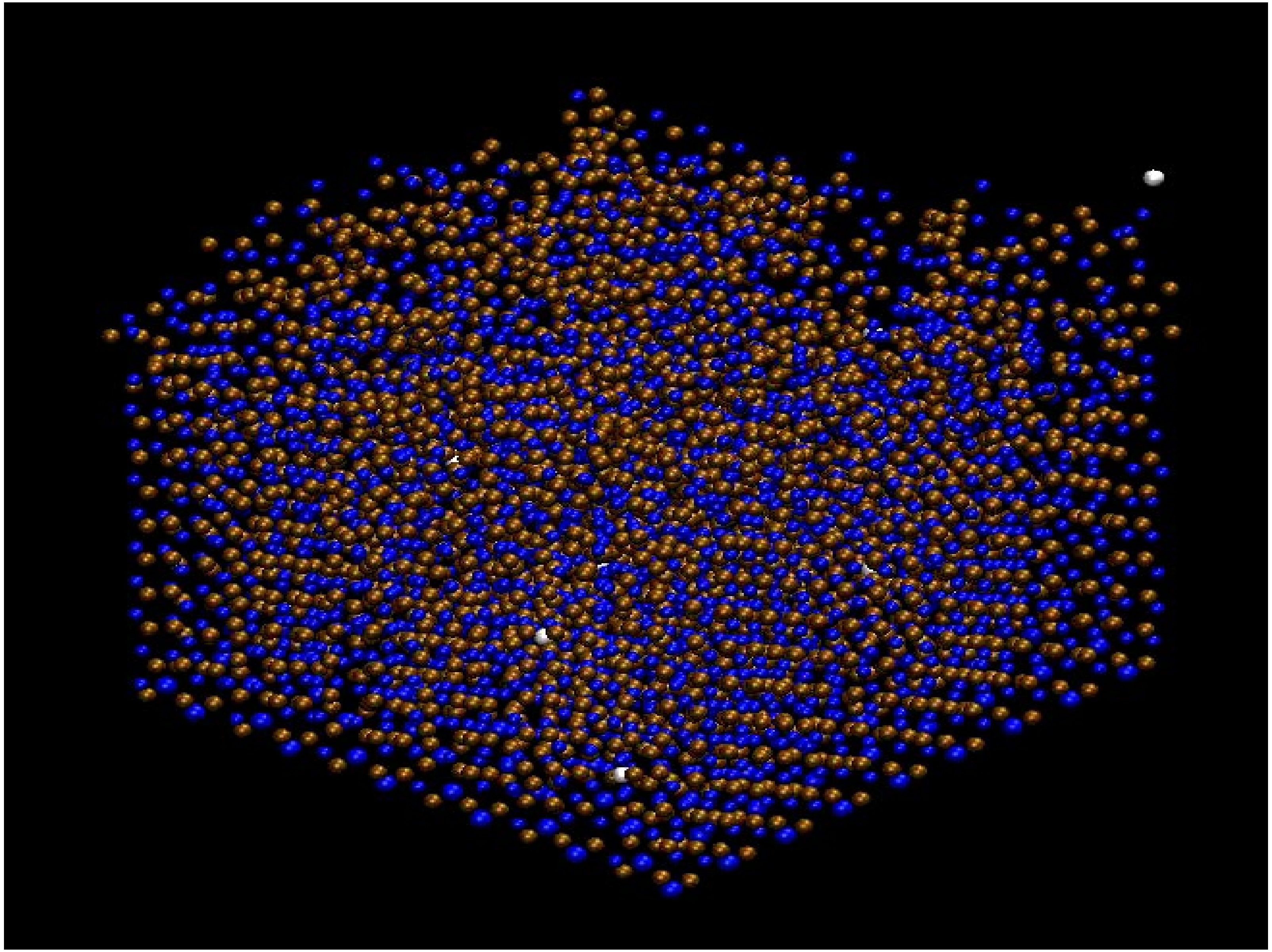
Erosion of Hall Thruster Channel



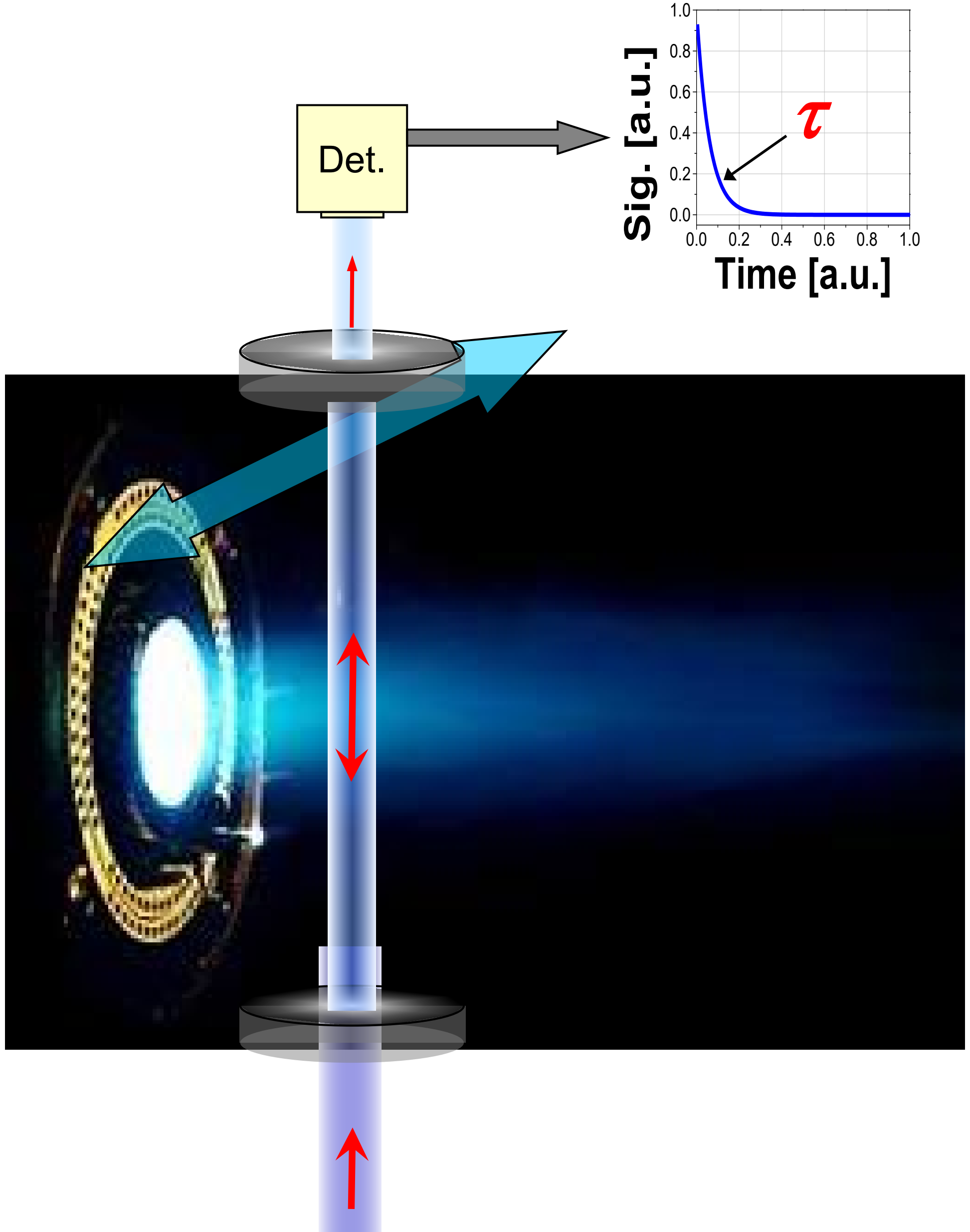


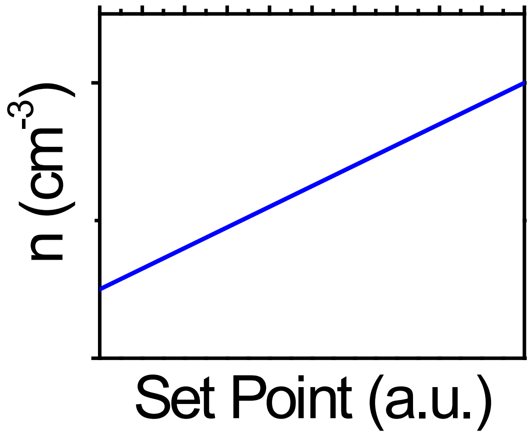
Sputter erosion of the ceramic wall slowly destroys the thruster!

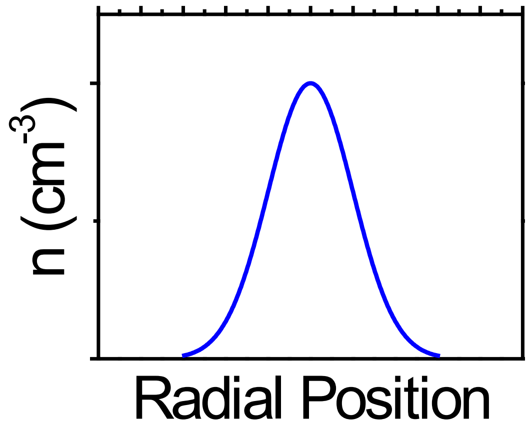
Molecular Dynamic Simulation of Boron Nitride Sputtering



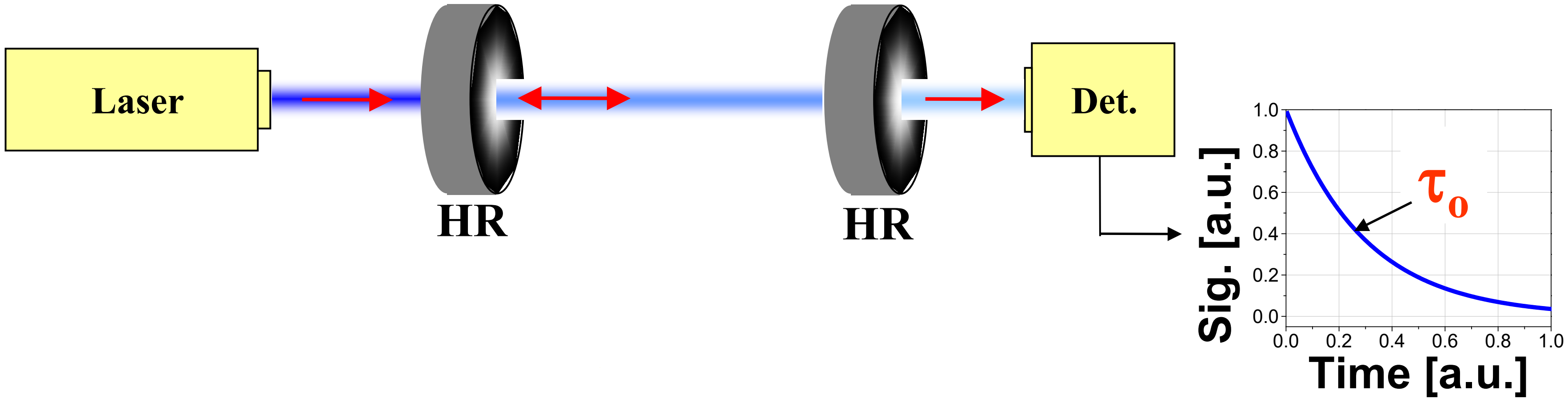
Real Time Thruster Erosion Sensor - CRDS

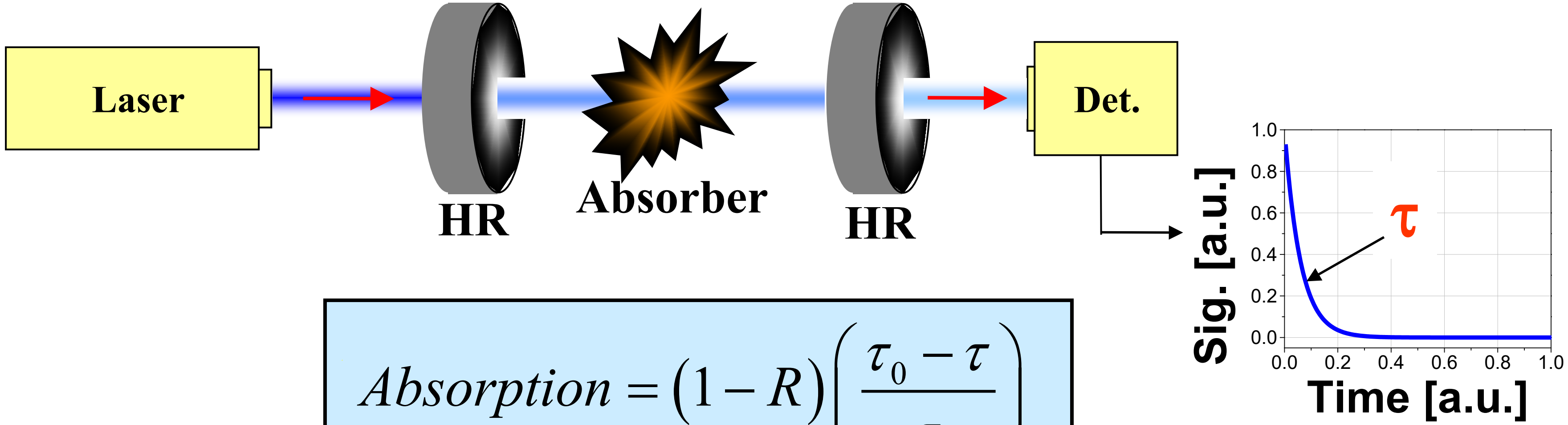






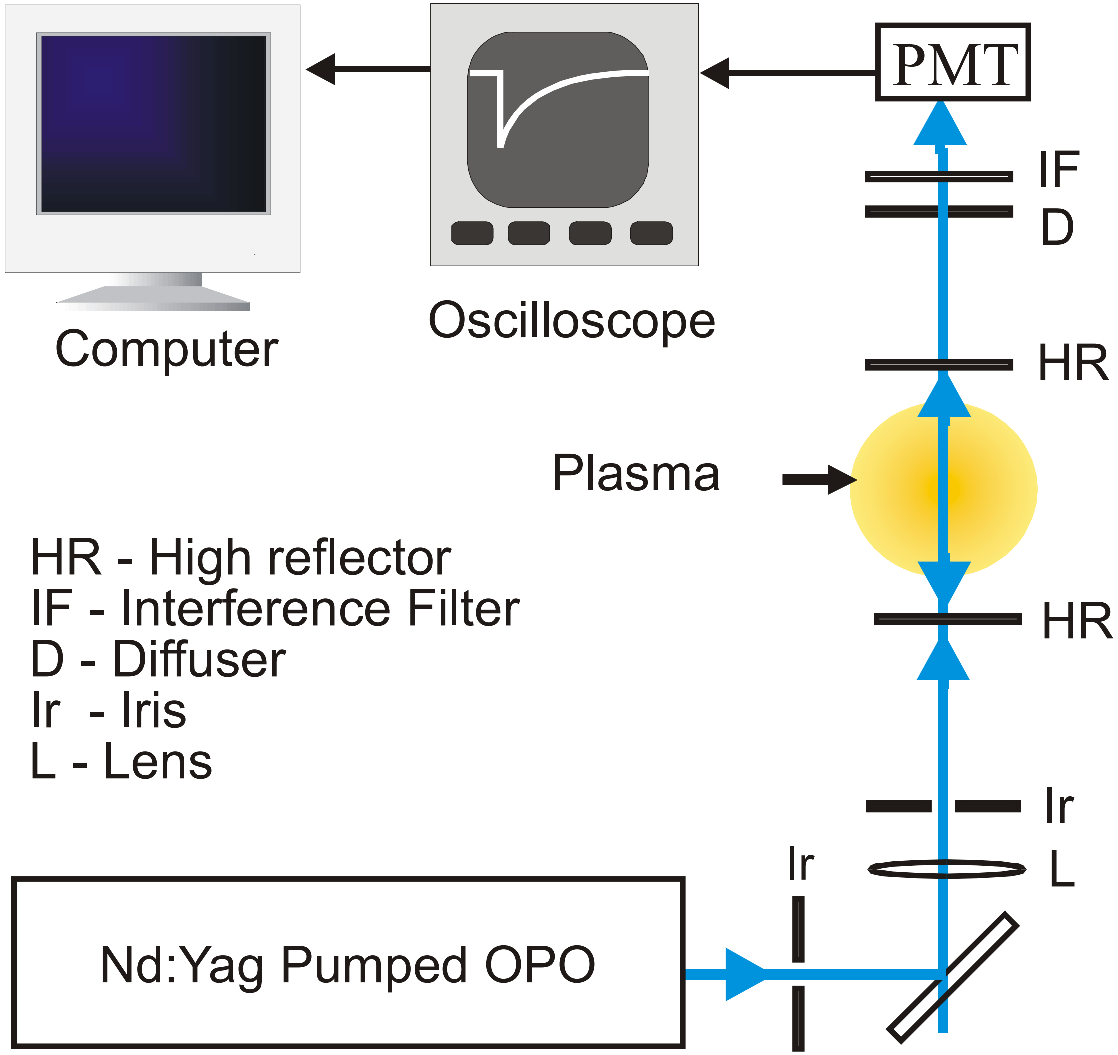
Cavity Ring-Down Spectroscopy





$$Absorption = (1 - R)\left(\frac{\tau_0 - \tau}{\tau}\right)$$

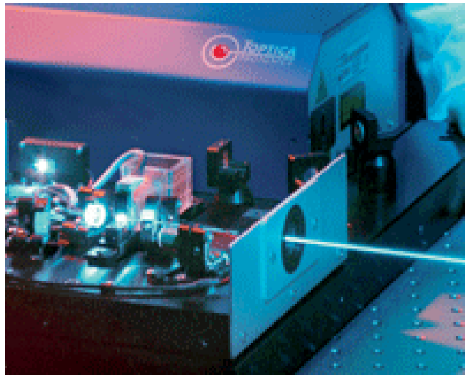
Typical CRDS Setup

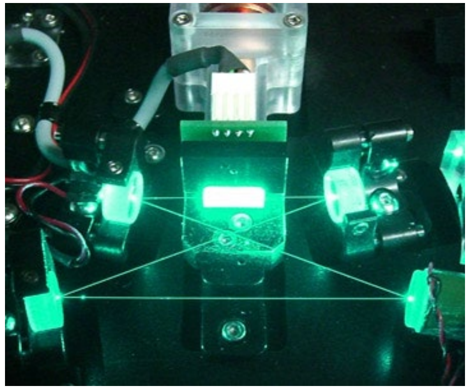


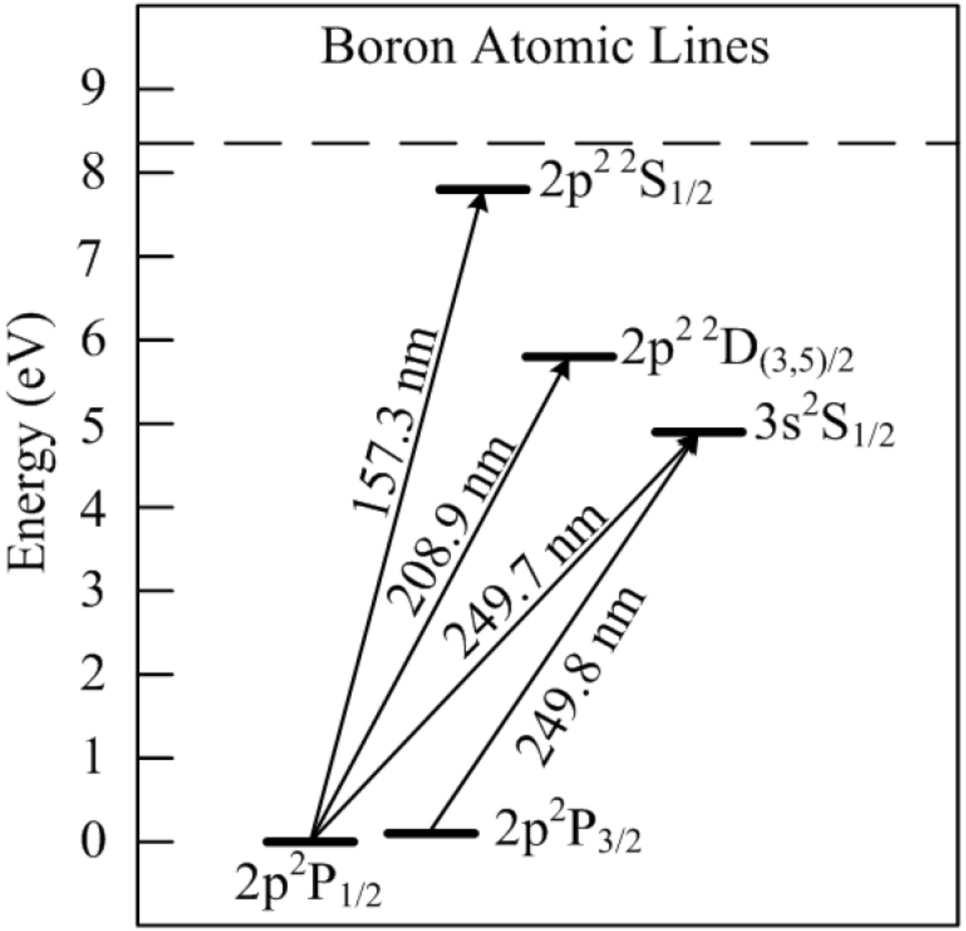
Boron Spectroscopy

Use the $2p^2P_{3/2} \rightarrow 3s^2S_{1/2}$ line at 249.8 nm

- Ground state transition
- 2/3 of population in J=3/2 state
- Optically accessible with frequency quadrupled laser







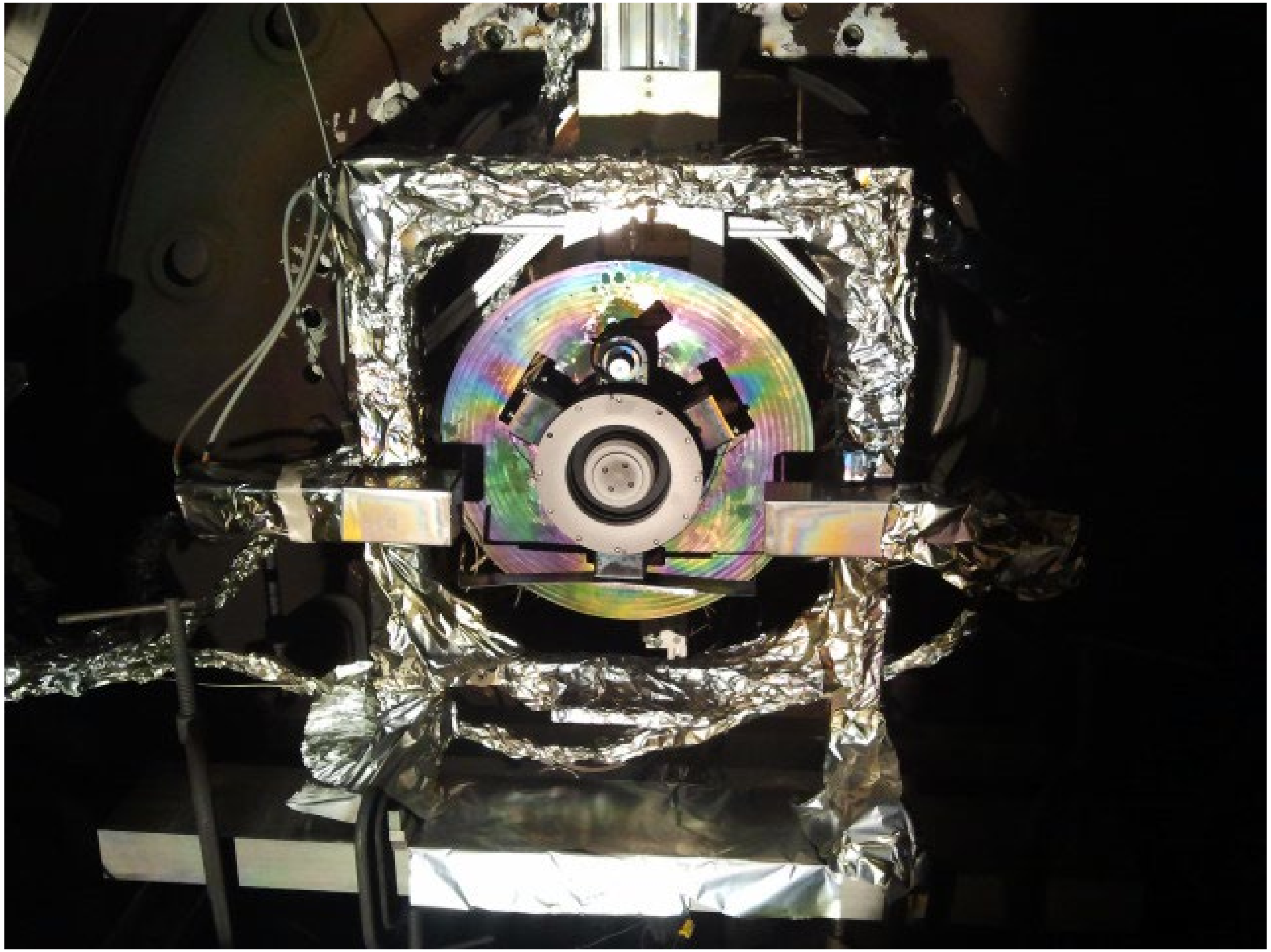
Partial energy level diagram for neutral atomic boron.

Erosion Measurements of NASA HiVHAc (NASA GRC)

- Designed as low-cost solution to Discovery class missions
- Mission studies showed HiVHAc can close missions other Hall thrusters could not[1]
- Power of 0.3 to 3.9 kW, up to 650 V_d
- Test performed on Engineering Development Unit 2 (EDU 2)

[1] Dankanich, J. W., et al., IEPC, 2009-213, 2009.

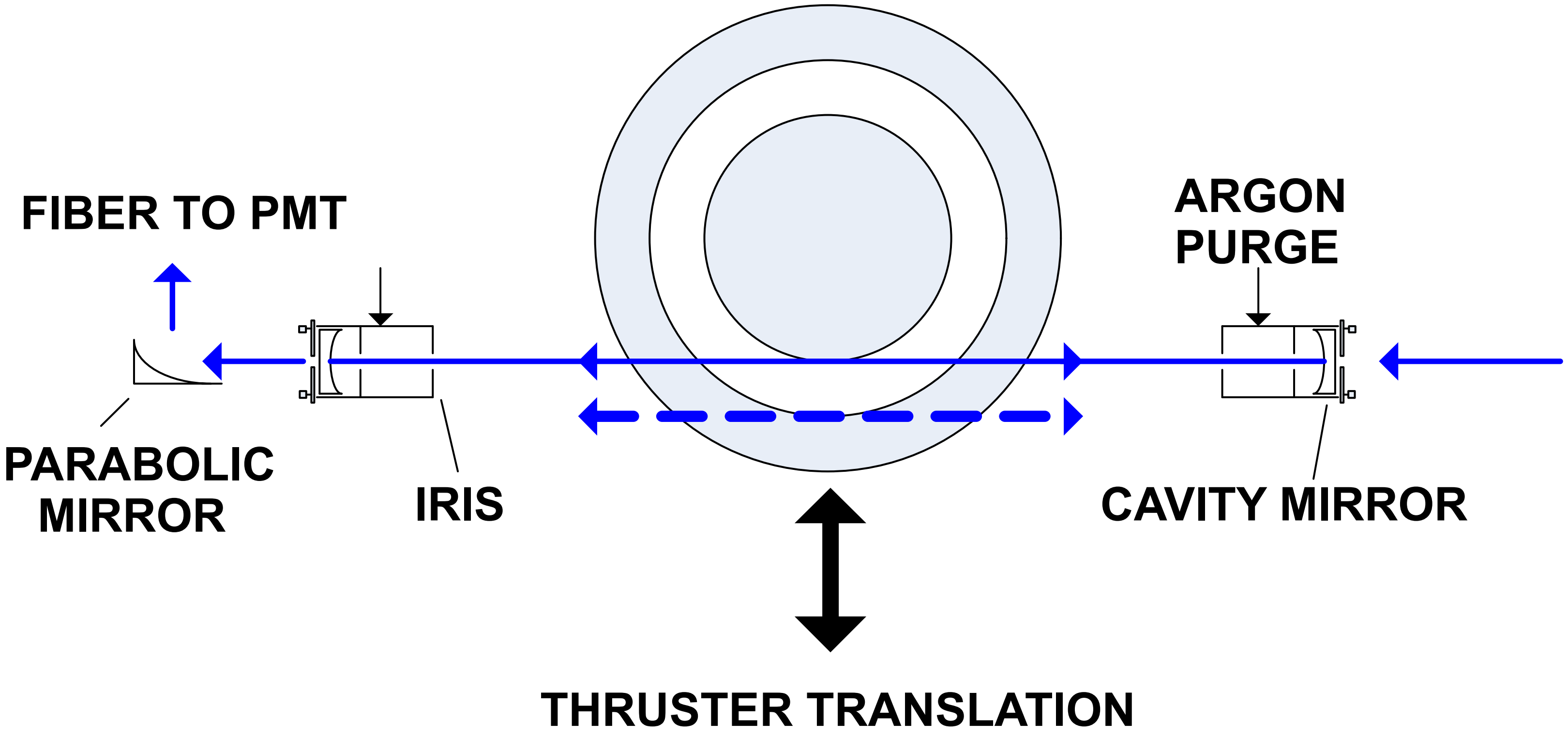
Erosion Measurements of NASA HiVHAc (NASA GRC)



Tested in GRC's VF-8:
- 4×10^{-7} Torr base pressure
- $1\text{-}2\times10^{-5}$ Torr operating pressure
- 1.5 m Diameter, ~5.5 m long chamber

Thruster set points:
- Power of 1, 1.5, 2, 2.5, 3 kW at V_d=500 V
- V_d=330, 400, 500, 600 V at Power=2 kW

Vacuum Side Optics (cw-CRDS)

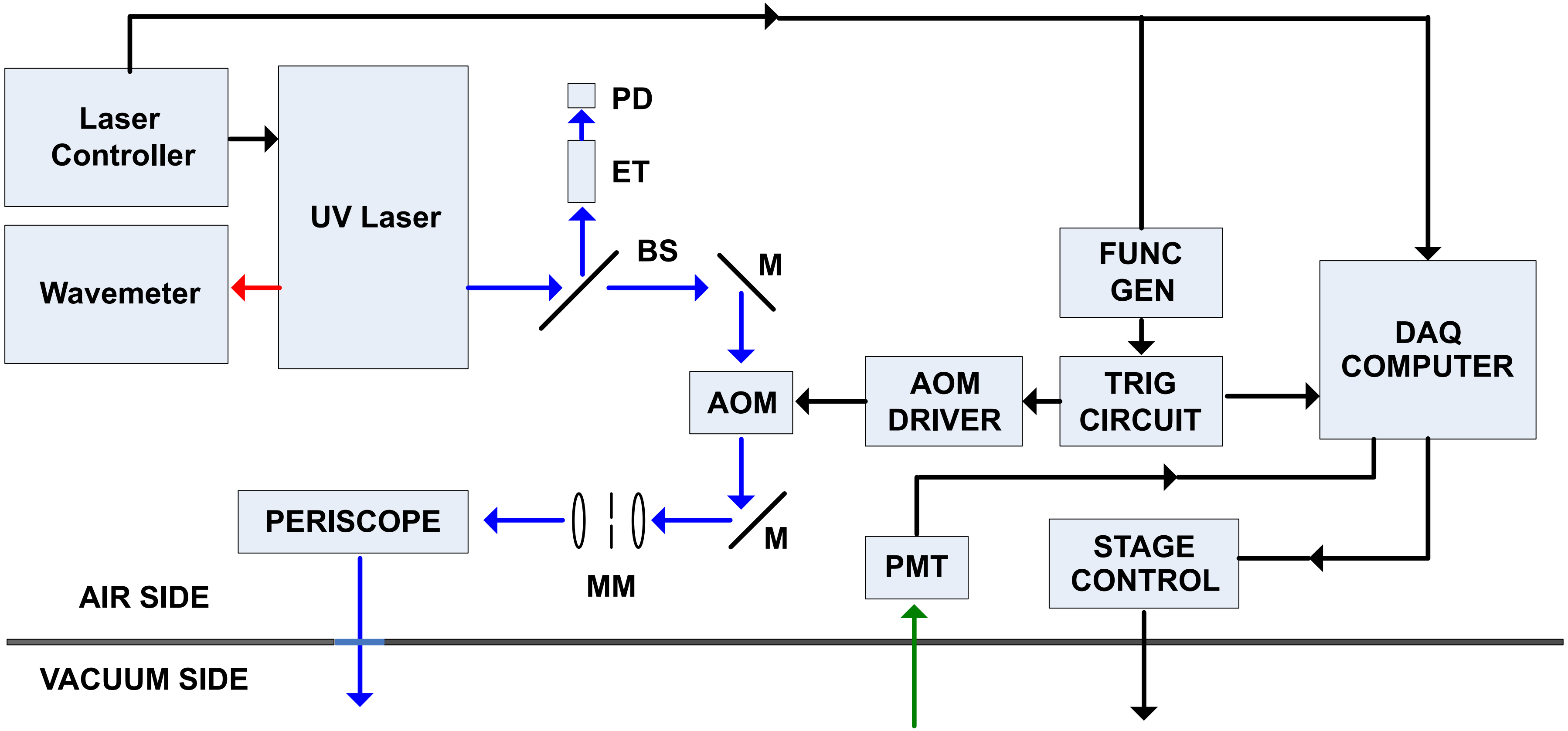


Note on non-dimensionalized thruster position :

Corresponds to P=0

Corresponds to P=1

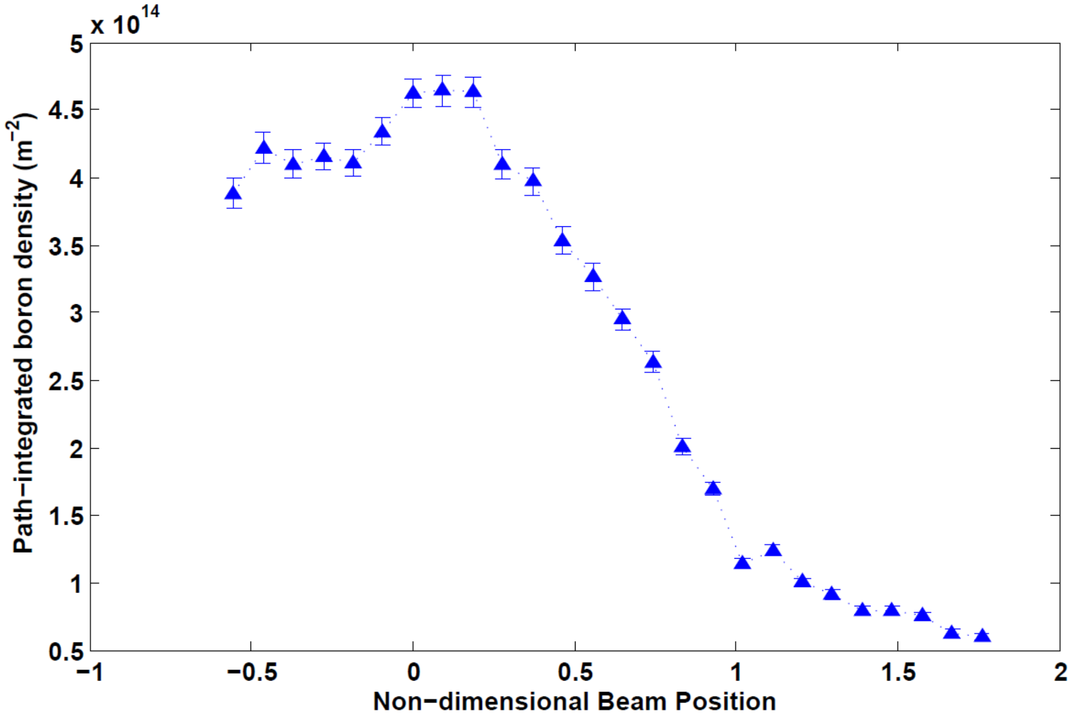
Air Side Optics (cw-CRDS)

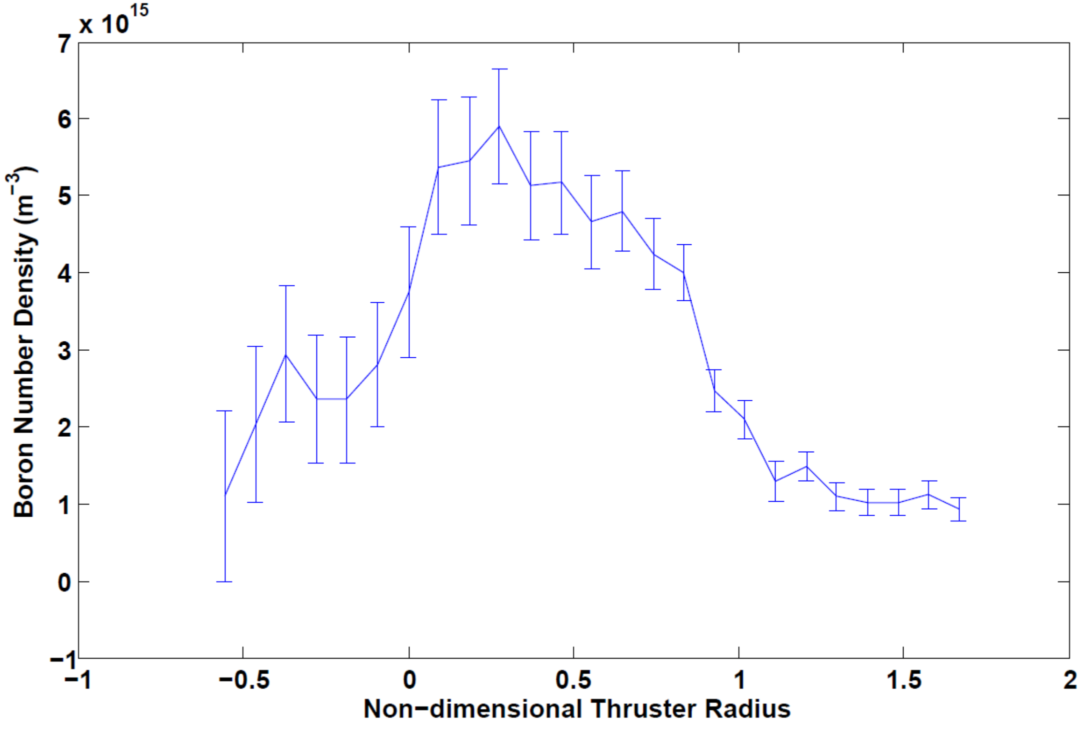


BS: Beam splitter
PD: Photodiode
ET: Fused silica etalon
M: Mirror

AOM: Acousto-optic modulator
MM: Mode-match telescope
PMT: Photomultiplier tube

Boron densities: Path-integrated and Radial

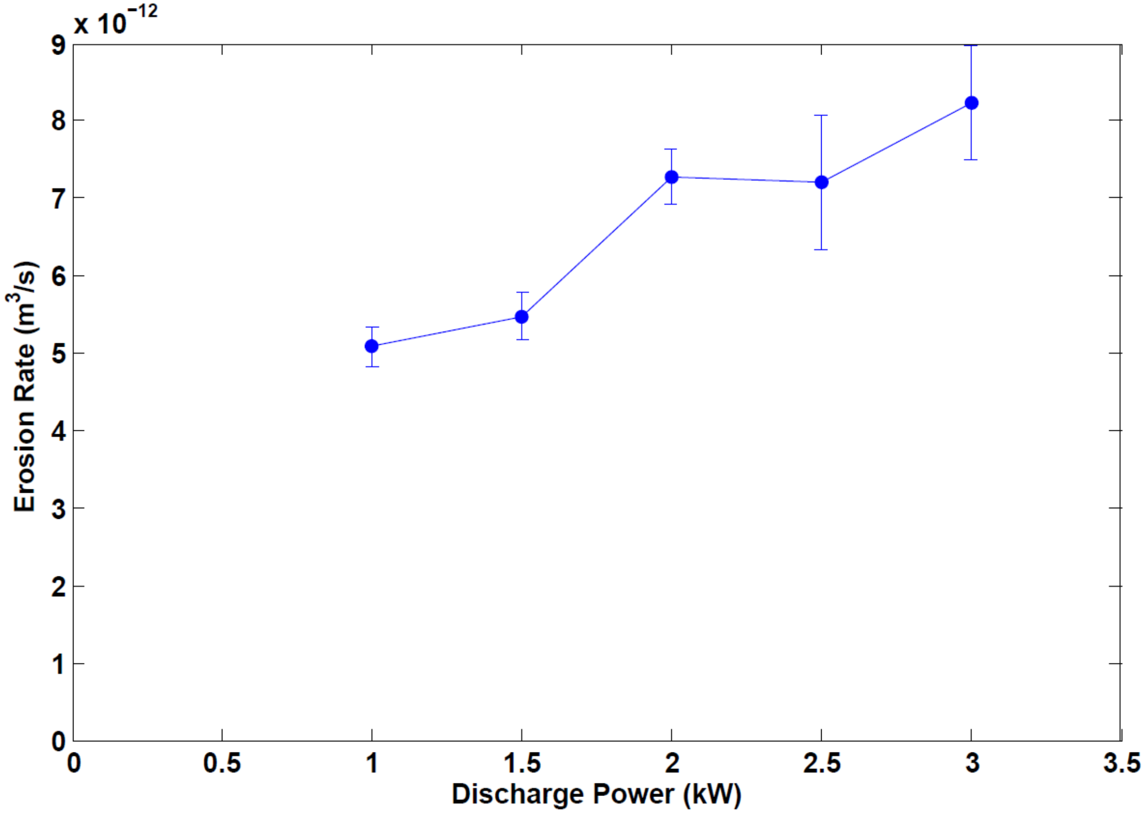




- Area under spectrum → Path-integrated Boron Number Density
- Error bars from statistical noise only (systematic errors discussed later)
- ~5-30 min per thruster set point

•Radial concentration profile after matrix inversion
•Only statistical noise considered for error bars
•Reminder: R=0 is inner channel; R=1 is outer channel

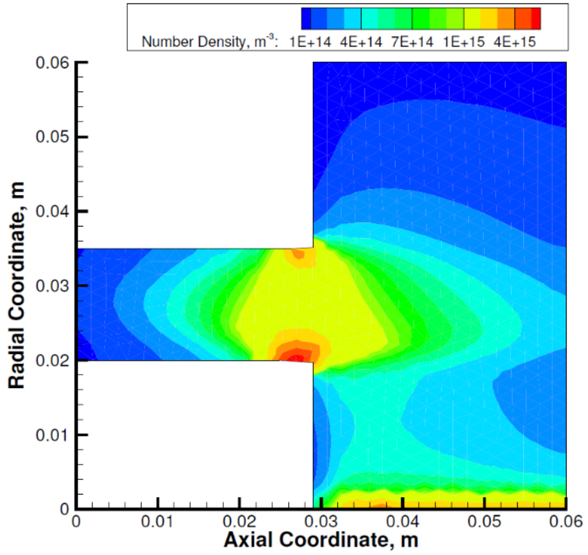
HiVHAc Channel Erosion Rates



Erosion rate at constant 500 V as discharge power varied

B. Lee et al. "A cavity ring-down spectroscopy sensor for real-time Hall thruster erosion measurements" Rev Sci. Inst. 83, 123503 (2012)

- Erosion (flux) estimation require density and speed. Speed was from LIF measurements (~10 km/s).
- Also found reasonable agreement with numeric model (Monaco):



H.C. Dragnea, I.D. Boyd, B.C. Lee, A.P. Yalin "Characterization of Eroded Boron Atoms in the Plume of a Hall Thruster" IEPC-2013-158, 33rd Electric Propulsion Conference (2013)

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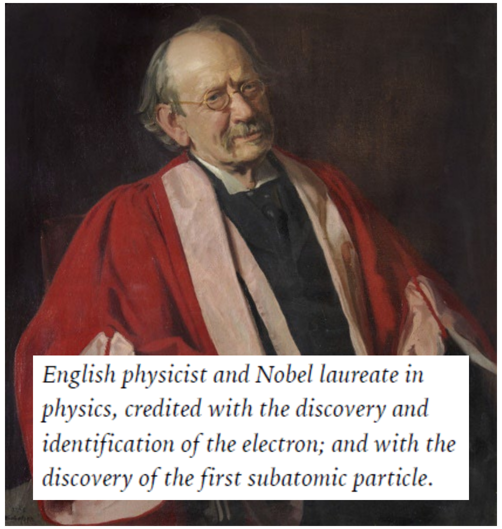
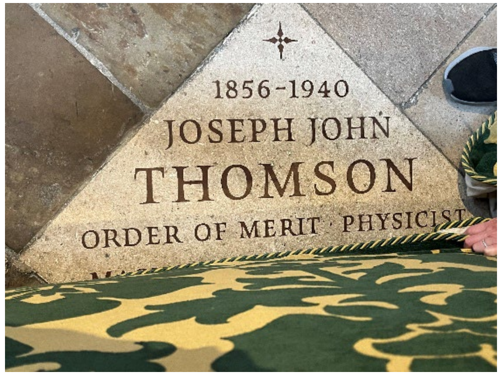
Laser Thomson Scattering (LTS)

Thomson scattering is the elastic scattering of electromagnetic radiation by a free charged particle. The electric field of the incident wave (photon) accelerates the charged particle, causing it, in turn, to emit radiation at the same frequency as the incident wave, and thus the wave is scattered.



English physicist and Nobel laureate in physics, credited with the discovery and identification of the electron; and with the discovery of the first subatomic particle.



- Elastic, non-relativistic scattering by electrons.

$$m_e\vec{a} = -e\vec{E}(t)$$

- Accelerating charge radiates (Larmor).
  - Also dipole radiation.

$$\Delta z \approx \frac{1}{2}at^2 \approx \frac{e}{2m_e}|E|\left(\frac{c}{\lambda}\right)^2$$

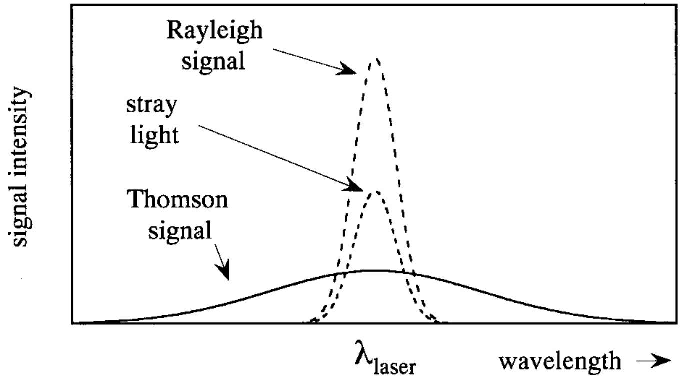
$$\Delta z \approx 0.1\ nm\ \ (|E| = 1\frac{MV}{cm}, \lambda = 1\ \mu m)$$

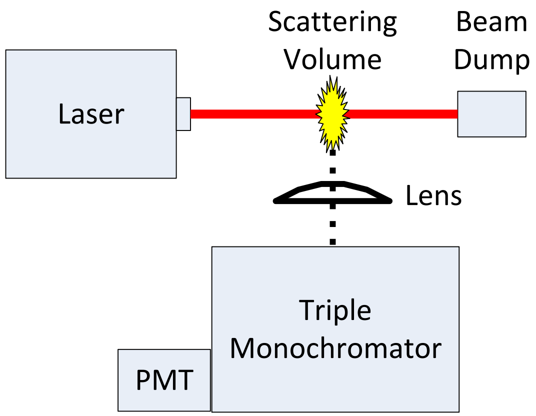
- Also coherent w.r.t. source.

- Total cross-section: $\sigma_T = \frac{8\pi}{3}\left(\frac{e^2}{4\pi\epsilon_0 m_e c^2}\right)^2$

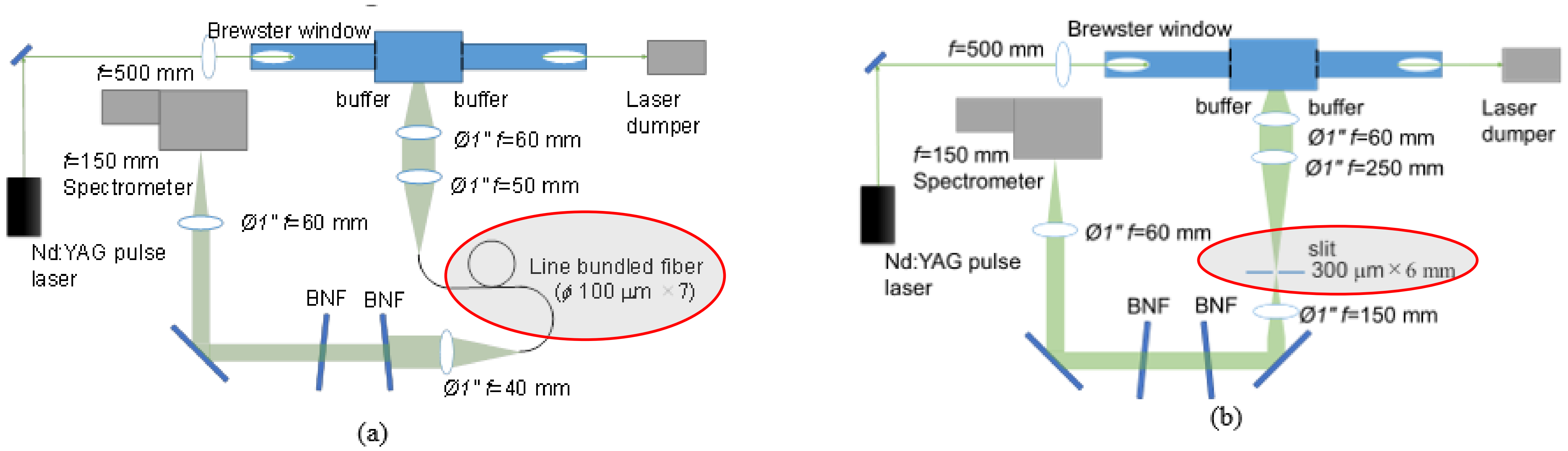
$$= 6.65246 \times 10^{-25}\ cm^2$$

Credit: C. Limbach, AIAA SciTech Plasma Diagnostics Short Course, 2019





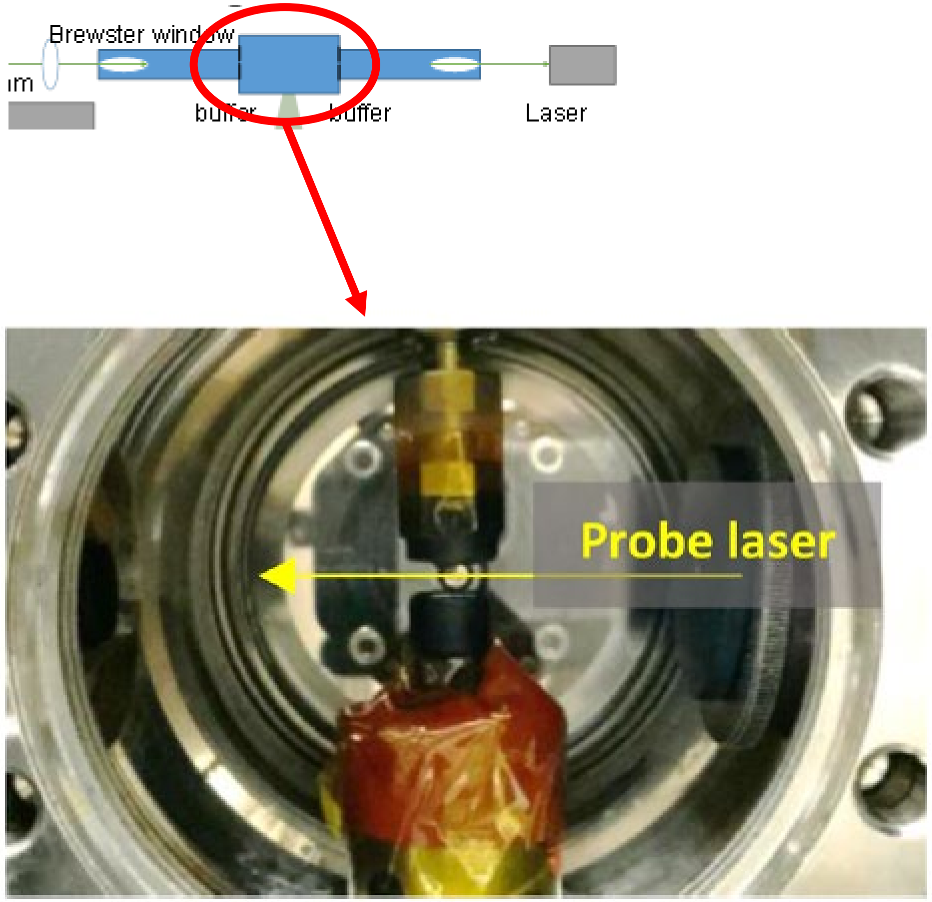
Compact LTS Setup (2 versions)

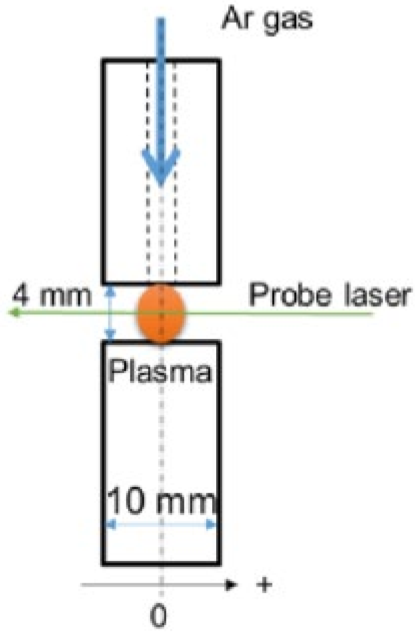


- Probe laser: Compact Nd:YAG at 532 nm, 50 mJ, 20 Hz.
- Spectrometer: f=150 mm, 1800 grooves/mm, 150 μm entrance slit (dispersion of 2.37 nm/mm)
- **Stray light suppression: 2 Bragg notch filters (BNF) with precise angular alignment.**
  See: Vincent et al., PSST 27 (5) 2018
- **Light collection and filtering by 2 approaches: a) linear fiber bundle, b) slit spatial filter.**
- Signal measurement: ICCD camera (q.e.=45% at 532 nm). 5 sets of 2,000 accumulated signals were used to analyze the Thomson spectra.

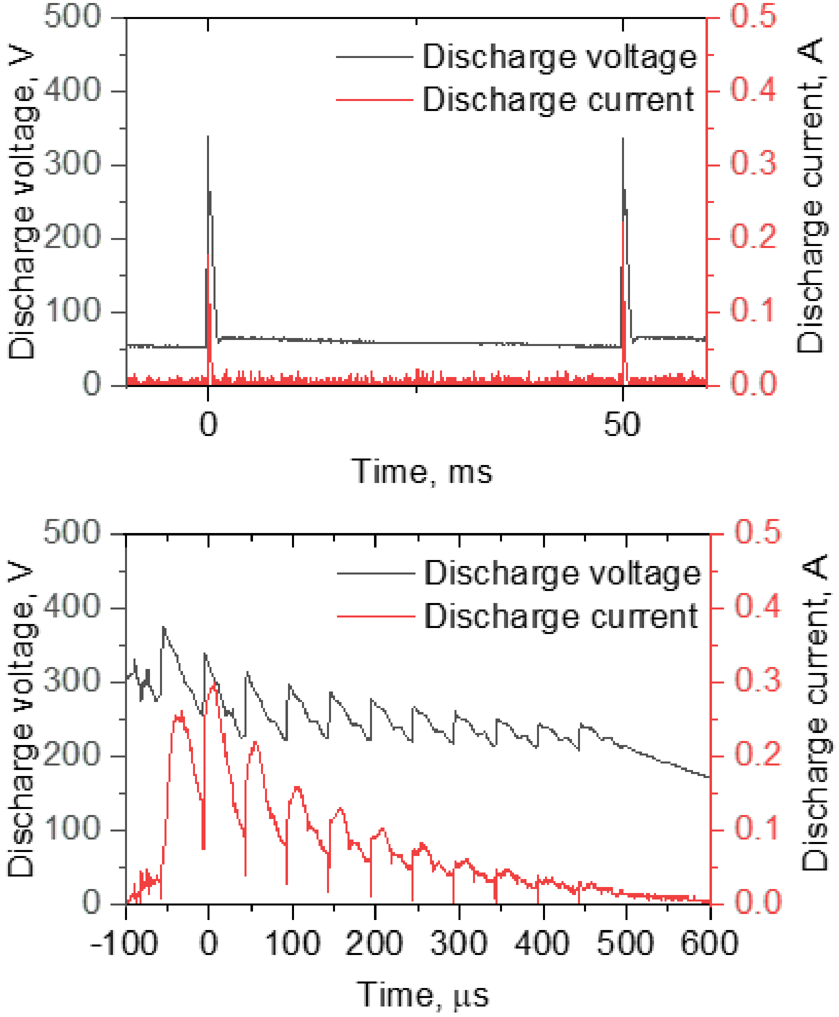
Pulsed Plasma Source

- Glow discharge ion source operating with pure Argon gas
- Time-resolved studies use AC power supply operating at 20 kHz. Diode circuitry use to ignite the plasma at 20 Hz to match laser; plasma duration of ~ 500 μs.

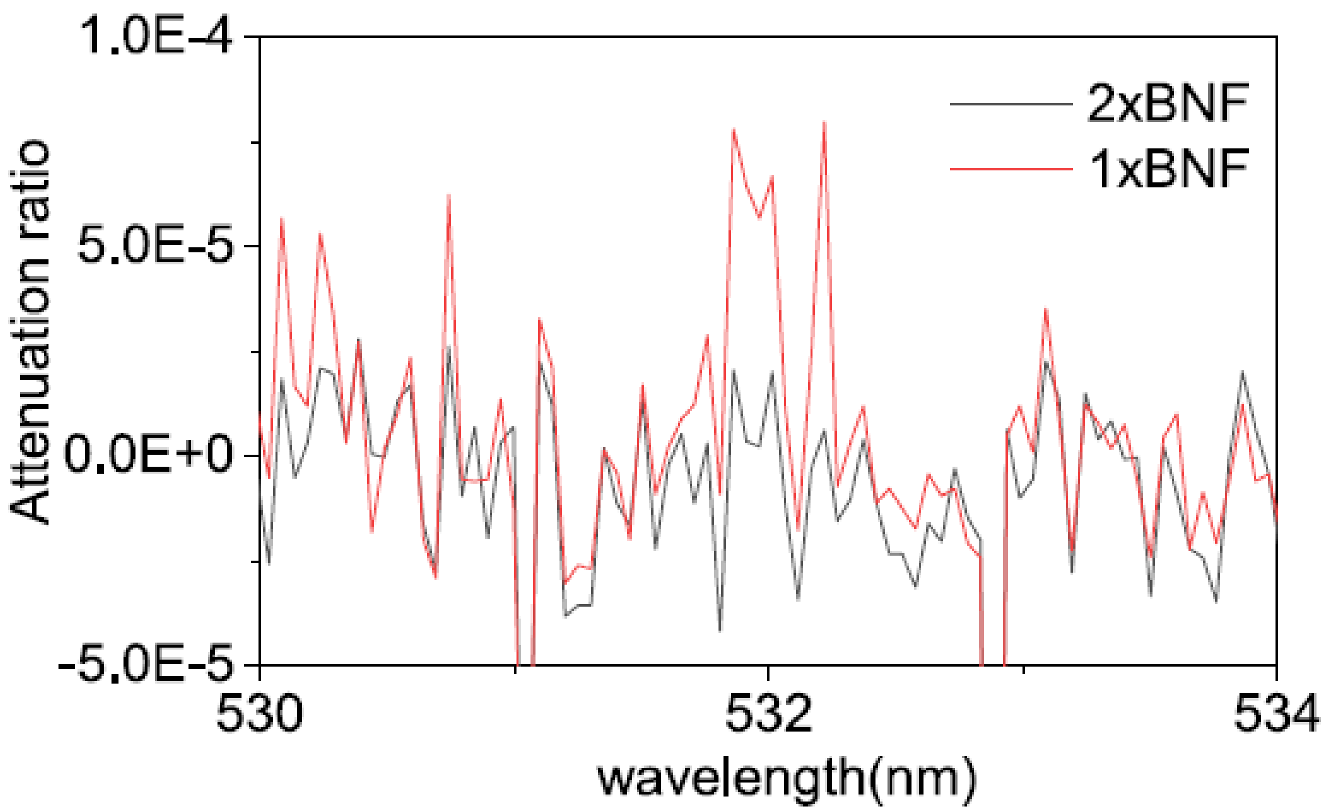




Voltage Waveforms

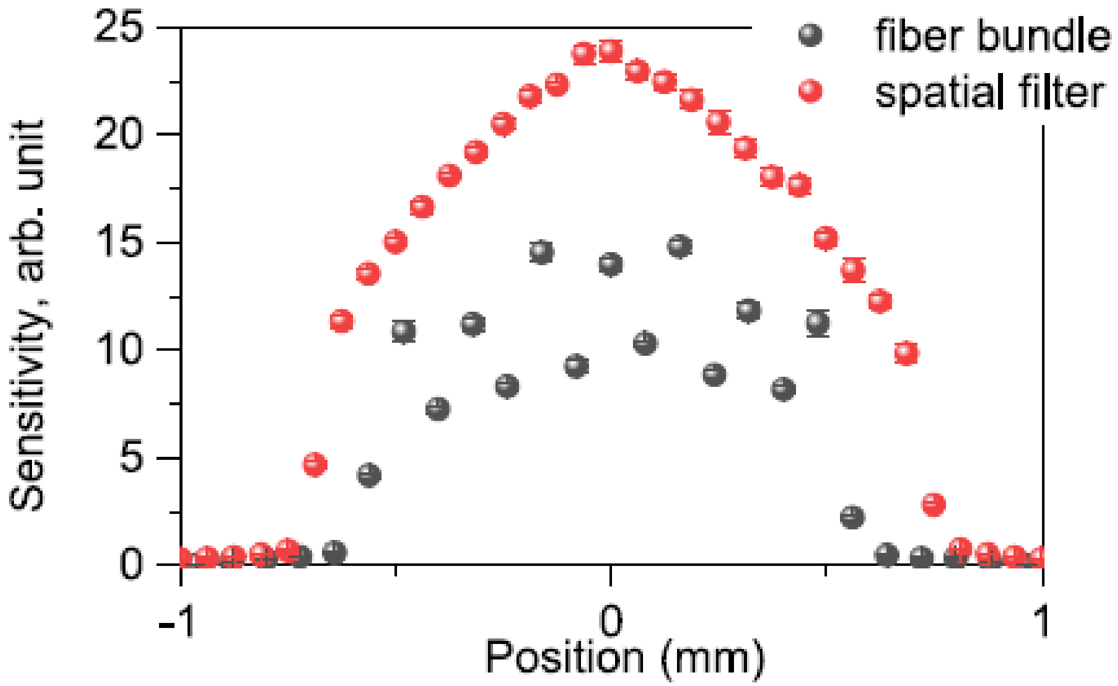


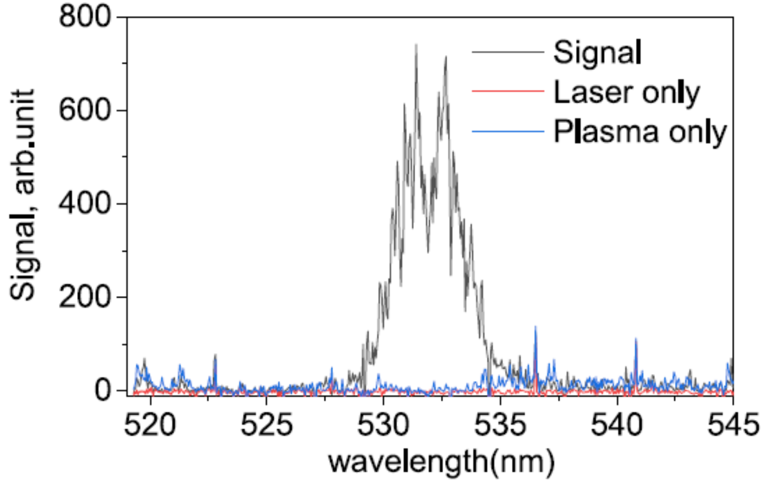
Attenuation (Relative to Rayleigh peak at 300 Torr)



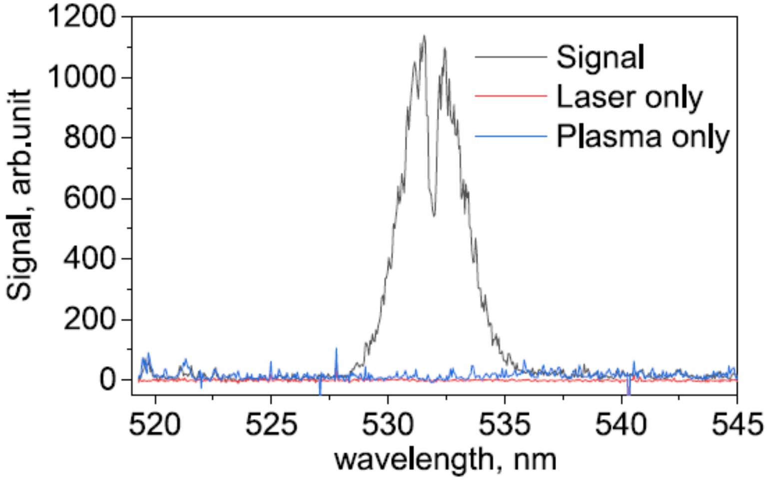
- Strong suppression (>~10^4) both in and out of filter band.
- Negligible stray light (532 nm) with 2 BNFs.

Spatial Sensitivity and Example Spectra





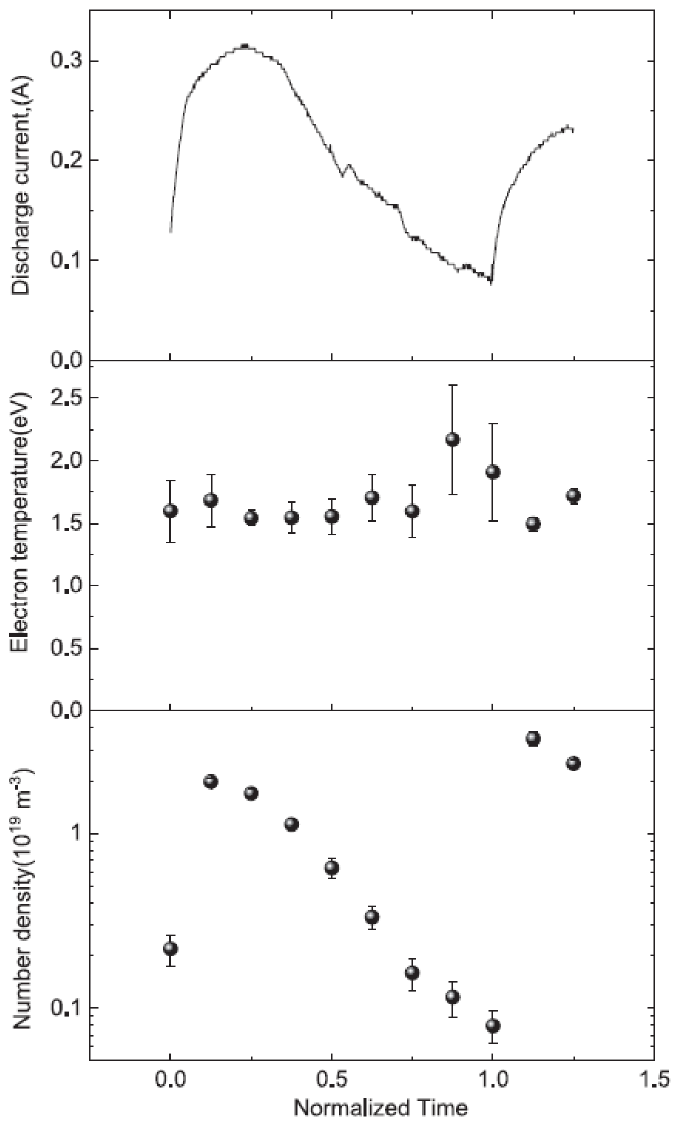
(a) fiber bundle

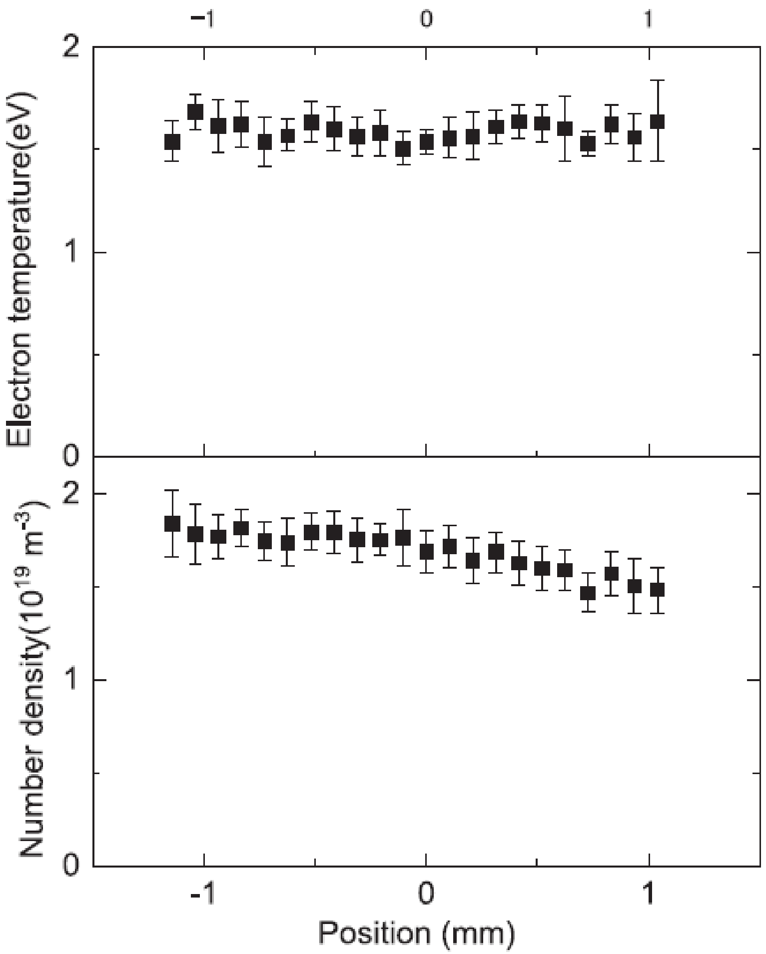


(b) slit spatial-filter

- Somewhat better performance with slit versus fiber.

Spatially- and Temporally-Resolved Laser Thomson Results





- Time-axis is normalized by the period (50 μs).
- Spatial data at t=12.5 μs.
- Highly resolved data obtained at EP relevant conditions.
  - Detection limit of n_e~10^{11} cm^{-3} (~10 min.)

Portable Thomson scattering system
for temporally resolved plasma measurements
under low density conditions

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Submitted: 10 October 2023 • Accepted: 12 February 2024 •
Published Online: 7 March 2024

N. Yamamoto[1] and A. P. Yalin[2,a)]

Summary

- TALIF allows spatially- and temporally-resolved neutral density (e.g., Kr and Xe) by directly probing the ground state.
  - Cathode measurements reveal interesting flow-field physics.
  - HET measurement allow spatial maps of neutral density.
  - Captured neutral oscillation (ground state) of Hall effect thruster Breathing Mode for first time.
- Extended to TALIF flow-tagging velocimetry for direct measurement of motion of (ground state) atoms (cf LIF methods).
  - S:N in plasma can be improved with c-w laser for READ step.
- <u>Future work:</u> High-power thrusters, spatially resolve along thruster axis, velocimetry in HET, molecular propellants.

- CRDS allows detection of trace species (e.g., sputtered species, impurities) at very low densities (~10^7 cm^{-3}).
  - CRDS measurements are self-calibrating. A short-coming is that measurements are path-integrated.
  - Useful to characterize channel erosion (but less needed due to Magnetic Shielding).
- <u>Future work:</u> CRDS studies of cathode materials, e.g. Ba from BaO cathodes.

- LTS is a powerful non-intrusive diagnostic allowing measurement of electron properties (density and temperature).
  - A compact system based on small laser, 2 VBGs, and single-stage monochromator shown at EP-relevant conditions.
  - Plasma perturbations must be carefully considered but can usually be avoided.
- <u>Future work:</u> Implement on HET, fusion plasma systems.

Many research avenues for laser diagnostics for Low Temperature Plasmas!!

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- CSU EP graduate students: Vijay Surla, Lei Tao, Brian Lee, Adam Friss, Tad Wegner, Jacob Gottfried, Seth Antozzi, Seth Thompson, Jon Stienike
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